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Measuring and understanding receiver efficiency in your acoustic telemetry array

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ABSTRACT

Methods to evaluate receiver performance within acoustic telemetry arrays are needed to quantitatively determine which receivers are the most important to maintain. A recently developed approach, the Receiver Efficiency Index (REI), expresses the proportion of transmitter activity from throughout an array that occurs at each receiver location within it. The components of this composite index equally weight the proportion of detections, individual tags, and species from the entire array that were detected at a given receiver and then adjusts for the proportion of time that each receiver was deployed. In this study, we evaluated receivers in a long-term (8+ years) telemetry array deployed in Gray's Reef National Marine Sanctuary (GRNMS) located off the coast of Georgia (southeastern USA). Specifically, we explored the causes of fluctuations in the index over time, evaluated correlations between the REI and its component measures, and determined the sensitivity of the composite to individual components. Additionally, we examined the fish assemblages detected at each receiver over time using non-metric multidimensional scaling (nMDS) to assess how REI scores vary across fish communities. Results indicate that receiver importance varied through time. Correlations between the REI and each of its components were all positive and significant, and the REI was robust to exclusion of any one component. Sites with similar fish assemblages had very different REI values in GRNMS, but not when we reexamined the data from an array in Florida that was used to develop the REI. These findings suggest that decisions regarding which species groups (e.g. resident versus transient), time periods (e.g. seasonal versus inter-annual), or even components of the REI (e.g. duration of deployment) to include during analysis can have strong effects on the interpretation of receiver importance. We also recommend that the REI be coupled with species assemblage analyses such as nMDS to better understand how fish assemblages differ at sites with similar REI scores.

1. Introduction

Acoustic telemetry studies typically rely upon an array of multiple receivers strategically positioned throughout a region of interest to monitor movements of aquatic animals that are implanted with acoustic transmitters. Their initial placement is often guided by anticipated detection range, advice from telemetry veterans, and the best professional judgement of the researchers involved. Depending on the particular species, research questions, and physical arrangement of the study region, receivers can be deployed in a gate formation to track movements across a line, in a regular grid to track general movements, or more deliberately near discrete features or corridors of interest (Heupel et al., 2006). In all cases, these receivers represent a finite resource that must be efficiently placed to get the most information for the least expense (i.e. cost of hardware, maintenance, and field operations) (Clements et al., 2011; Kessel et al., 2013). Whether after a pilot study or as arrays are reconfigured to address different objectives, the specific positions of receivers are subject to modification and improvement using knowledge gained during prior deployments. Even arrays being decommissioned may benefit from maintaining a handful of

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receivers at strategic locations to sustain long-term monitoring and collaborative endeavors. As a result, methods to compare the relative value of receiver positions within an array are needed to quantitatively determine which receiver locations are the most important to maintain.

Simple metrics such as number of detections, number of individuals, or number of species recorded at each receiver location can be partly relied upon to determine which locations provide the most cost-effective deployment. When compared among receiver locations or to the array as a whole, these metrics can provide some insight into the relative importance of individual receivers. However, each of these metrics is biased in different ways. For example, the number of detections can be skewed by a few highly resident or sedentary individuals and thus may conceal locations used by many individuals but only temporarily. The number of individuals detected at a location reveals sites that are frequently visited but may also mask important aspects of duration of stay and the diversity of visitors. Including species-richness per receiver location solves the problem of diversity, but then conceals the relative abundance of the various species and their residence time. Each of these metrics is useful individually or in concert, but ideally a more holistic value may prove more informative. A new index called the Receiver Efficiency Index (REI) was recently developed that incorporates all three data types (i.e. number of detections, individuals, and species) into a single metric (Ellis et al., 2019).

The REI was inspired by analogous challenges faced by researchers analyzing gut contents of fishes. Diet can principally be described based on the number or volume of various food items, however, those measures may lead to the outcome where many of a small food item are confusingly compared to a few of a larger one. The Index of Relative Importance (IRI) was developed by Pinkas et al. (1971) to address this challenge by combining both these measures along with their frequency into a single holistic value that is now widely used in diet studies (Hart et al., 2002). Similarly, the REI seeks to quantify the relative importance of receiver locations in an acoustic telemetry network by incorporating multiple and potentially conflicting aspects of detection data into a single composite value for each receiver.

The REI is calculated for each individual receiver location (*r*) within an array (*a*) using the 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 a specific receiver (D_r) was deployed within an array (D_a) (Ellis et al., 2019). Thus, T_r/T_a represents the proportion of the tagged individuals detected throughout the entire array that were detected at a given receiver. Similarly, S_r/S_a is the proportion of species detected in the array that were detected at that receiver, and DD_r/DD_a is the proportion of all the detections days from the entire array that were detected at the receiver. All three of these terms scale as proportions (0–1.0) with higher values denoting more activity at receiver locations. The last term, D_a/D_r, is a correction factor that adjusts for the proportion of time that a given receiver was actually deployed. For example, if a receiver was deployed for the same amount of time as the entire array (e.g. 1 year or 365/365 = 1), then the REI for that receiver is essentially unadjusted. Whereas if a receiver was present for less time than the entire array (e.g. half the year 365/183 = 2), its T, S, and DD values would be scaled upward (i.e. doubled, in this example) to the levels they would have achieved had the receiver been deployed for the entire duration of the array. This correction factor relies on the simplifying assumption that detection rates are uniform across the entire timespan of the array. Thus calculated, the REI is essentially a way to express the proportion of transmitter activity from an array that occurs at each receiver location.

One aspect of detection data not addressed by the individual metrics listed above or by composite metrics like the REI, is community composition. Two receiver sites may have the same quantity of detections, individuals, number of species, and REI values but the actual assemblage of species that were detected may be completely different. The similarity of the species assemblage detected at receiver locations is best evaluated through multivariate techniques such as the Bray-Curtis similarity coefficient, cluster analysis, and multi-dimensional scaling (MDS; Clarke and Warwick 2001). Analysis of assemblage composition among receivers would reveal how sites with otherwise similar attributes differ, and specifically convey which species are detected at each site (West et al., 2003 and Jaworski and Ragnarsson, 2006 provide analogous analysis for diet studies). Knowledge of which species or fish communities are more likely to be detected at a given site may be an important consideration when deploying limited receiver assets.

In this study, we evaluate the REI using data collected from an array deployed at the Gray's Reef National Marine Sanctuary (GRNMS) located offshore from Georgia (USA) (Fig. 1). The data collected by the GRNMS array offers a contrasting set of conditions from those data collected from the Florida arrays that were used in the initial description of the REI (Ellis et al., 2019), and as such, may be useful to illustrate the properties of the REI and variables that can influence it. Specifically, the GRNMS array offers a longer time-series for analysis (8+ years), a focus on transient species, and relatively low habitat diversity, compared to the Florida arrays which had a shorter duration (just 2 years), a greater emphasis on resident species, and were deployed across a wider range of habitats.

Evaluating the relative value of receiver locations over longer time periods, on a seasonal basis, or from multi-year arrays may warrant some additional considerations. There is an ever-growing number and diversity of organisms tagged with acoustic transmitters and increasing collaborations among researchers studying them (Hussey et al., 2015; Crossin et al., 2017; Williams et al., 2019; Young et al., 2020). Consequently, the number and types of fish that may be detected in an array may increase and change significantly over time, thereby complicating analyses. The extent to which REI values may vary from year to year at

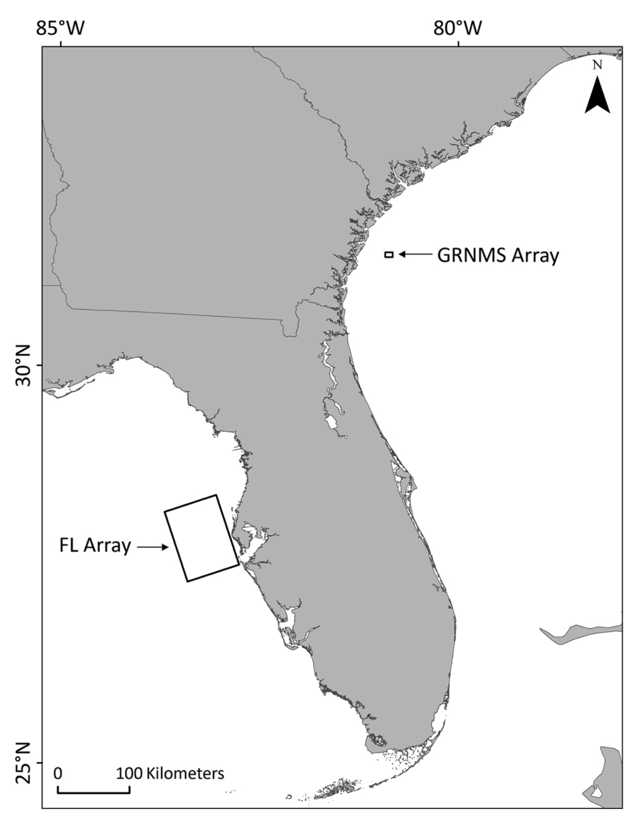

Fig. 1. Locations of the two study arrays off the coast of Georgia and the west Florida shelf.

the same location or may be consistent but actually represent different fish communities, has not yet been investigated. Additionally, the GRNMS data allow us to examine differences in receiver efficiency for arrays with primarily transient species in the detection data, compared to the Florida arrays that had a combination of both types (Ellis et al., 2019). Transient species, due to their migratory and mobile behavior, may exhibit brief stays and few detections at multiple receivers, in contrast to more sedentary resident species that may visit fewer receivers but provide many detections. Because we expect these species groups to load receivers so differently, they may merit separate analysis and definitions of what makes one receiver more efficient than another.

As was done for diet studies following the emergence of the IRI (Macdonald and Green, 1983; Liao et al., 2001; Hart et al., 2002), we seek to test REI performance compared to its basic component measures described above. We also consider species assemblage analyses that are not incorporated into the REI or other measures of receiver importance which may be useful when reconfiguring or down-sizing telemetry arrays. Specifically, we address the following questions using data collected from the GRNMS array: How does the REI correlate with its individual component measures (i.e., number of detection days, individuals, species, and deployment time)? How influential are these individual components to the overall REI calculation? How does REI change if considered holistically over the entire study versus in specific years or time periods? How do resident and transient species differ when evaluating receiver efficiency? How does assemblage composition differ among receivers and do those assemblages correlate with the REI or do they provide novel information when determining receiver importance? In addition, we assessed this last question using data from the west Florida shelf array that was used in the original REI description (see Ellis et al., 2019) to help contextualize how species assemblage information relates to REI. Our overall goal is to provide a set of comparisons and contrasting examples of implementing the REI with different datasets to better understand its performance in different situations.

2. Methods

Gray's Reef National Marine Sanctuary (GRNMS) is located ~30 km offshore of southeastern Georgia on the continental shelf in 18–21 m water depth and is comprised of a mixture of sand substrate, flat hard-bottom, and rocky ledge habitat (Kendall et al., 2005) which attract a diversity of fish fauna (Kendall et al., 2008, 2009, Williams et al., 2019). After a modest beginning with 4 acoustic receivers in 2008–2009 (Carroll, 2010; Mathies et al., 2014), the GRNMS array expanded to include a total of 30 unique receiver deployment locations from 2008 through 2017. Of these 30 total sites, only 11–20 sites were used concurrently, depending on the specific year (Roberson et al., 2020). Due to the ongoing maintenance of the receivers at GRNMS, the array amassed over 7000 detections from 164 individuals comprised of 18 different species not tagged in the sanctuary (Williams et al., 2019). To maximize the ongoing collection of detections of these transient species but reduce the burden of maintaining a large array, we seek to identify which receiver locations provide the most value so that the rest may be decommissioned and those receivers may be utilized elsewhere.

We also used detection data from the "reef array" deployed off the west coast of Florida described in Ellis et al. (2019). This array was deployed at artificial reefs, natural ledges, and hard-bottom habitats ranging in depth from 10 to 34 m and located from 12 to 55 km offshore. Life history characteristics, specifically the high site fidelity of two species tagged in the array, Goliath Grouper (*Epinephelus itajara*) and Gag (*Mycteroperca microlepis*), drove decisions about the initial array design (Collins et al., 2015). Receivers were deployed there from 2014 through 2015 at 29 unique sites that were operational between 415–730 days. Details on data compilation and filtering are provided in Ellis et al. (2019).

The REI, its component metrics, correlations among them, and assemblage analyses were conducted in R version 3.6.1 (R Core Team 2019). Only detection data from transient species were used in analysis of GRNMS data since maximizing efficiency of detections of those taxa was the primary objective. We split data into early (2010–2013) and late (2014–2017) years because the shape of the GRNMS array changed through time such that these intervals comprised two separate configurations. All sites were not deployed continuously throughout both configurations as receivers underwent maintenance. Data from 2008 to 2009 at GRNMS were not included in the analysis due to the small number and limited spatial extent of receivers deployed. REI values were overlaid on habitat maps of GRNMS from all years combined, from the early array configuration, and the late array configuration. Locations were ranked based on REI value for each time period and saved as a table to understand how their relative importance changed through time. In addition, because the number and variety of tagged individuals is gradually increasing on an annual basis (Hussey et al., 2015; Williams et al., 2019), we calculated REI separately for each year and plotted those values through time.

Individual components of the REI for the GRNMS receivers were calculated for each year separately while still adjusting for deployment span ($T_r/T_a*D_a/D_r$, $S_r/S_a*D_a/D_r$, and $DD_r/DD_a*D_a/D_r$). Pairwise relationships among the REI and each of these components individually were displayed in scatter plots for each array with the 1:1 line of agreement shown for reference. Statistical significance and correlation strength were determined using simple linear regression and Pearson's correlation coefficient (r). Correlations between the complete REI and REI calculated without each of its component terms were investigated in the same way.

In the initial REI publication, Ellis et al. (2019) demonstrated an approach to understand how many receivers are needed to accomplish various detection goals (e.g. 75 % of the species from the entire array; Steckenreuter et al., 2017). For this analysis, we used the same benchmarks at GRNMS and plotted the cumulative percentage of detections, species, and individuals against receivers rank ordered by REI. This was calculated separately for each array configuration at GRNMS (early and late) to see if results differed through time.

Lastly, because receivers with the same REI value could be detecting different communities, we conducted customized multivariate analyses to examine if and how community structure may differ among receivers at both the GRNMS and west Florida arrays. Analyses were conducted using the vegan package in R (Oksanen et al., 2019). First, the assemblage in each individual location-year combination for GRNMS was defined by the detection-days (DD) corrected for deployment time ($365/D_r$) from each transient species at that station during the corresponding year. Bray-Curtis dissimilarities were calculated among all assemblages and non-metric multidimensional scaling (nMDS) was used to understand relative similarity among assemblages. Symbol size in nMDS plots was scaled to REI value to visualize if sites with similar REI values had similar assemblages. Symbols also depicted two other attributes, year and location, to visualize which of these factors was most related to the observed nMDS pattern. Analysis of similarity (ANOSIM) was used to test if communities differed between low and high REI values (based on a natural break in the values where low – REI $<$ 0.05, and high – REI $>=$ 0.05), among locations or years.

The detection data from the west Florida array were separated into two groups: all fish, and non-target fish. The non-target group did not include detections of Goliath Grouper and Gag, which were tagged in the array. As was done with the GRNMS data, species assemblages for each site were defined by the number of detection-days corrected for deployment time for each species detected at each site, then visualized with nMDS. Symbol size in nMDS plots was scaled to REI value to visualize if sites with similar REI values had similar species assemblages. ANOSIM was used to test if communities differed by reef type (artificial or natural) and to test if communities differed between low and high REI values based on a natural break in the values at REI = 0.002 (low REI $<$ 0.002; high REI $>=$ 0.002).

3. Results

Spatial patterns in the REI values among receivers at GRNMS differed depending on the specific timespan considered (Fig. 2a–c). REI calculated over the entire time series (2010–2017) revealed that three sites –FS15, FS17, and Roldan – had the highest REI values overall (Fig. 2a) (Table 1). Using only the early years of the array (2010−2013), the pattern changes such that many more sites are apparently detecting a larger proportion of transmitter activity including sites in the south-east (e.g. 08C, 08D, W15, Roldan) and north-central (e.g. 09 MN, 09MS) regions of the sanctuary (Fig. 2b) (Table 1). However, using only the later years of the array, the patterns changed again such that a site in the middle of sanctuary – 09 T – had among the highest values (Fig. 2c) (Table 1). Considering all time intervals, sites on opposite sides (east and west) of the sanctuary along hardbottom edges, consistently had among the highest REI values.

The REI results at GRNMS also revealed complex spatial patterns in receiver importance, where sites close together, even in the same time period, did not necessarily have similar values. For example, despite being only 294 m away, Recon4 had a much lower REI than FS15 depending on which time interval is examined (Fig. 2a–b). Similarly, 09Y and 08C are only 488 m apart but may or may not have different REI values depending on the time period considered (Fig. 2a–b).

Examining annual REI values for each receiver at GRNMS demonstrates the variability in the magnitude of the REI both within and among sites, and how the sites with the highest REI change through time (Fig. 3). On an annual basis, either FS15 or FS17 always had the highest REI values, often twice as high as all other receivers. The receiver at FS15 dominated detection activity in the early years whereas FS17 had highest REI values during the later years. However, even in consecutive years, receivers could have very different REI values. For example, the receiver at the "Recon4″ site had the 9th highest REI value in 2012 but the 2nd highest REI value in 2013. Also of note and unlike other years, none of the receiver locations recorded a large proportion of detection data in 2015 since all sites have a low REI. Even FS15 and FS17 were not detecting large proportions of the array's transmitter activity in 2015, although those sites still had the highest REI values that year.

In 2017, station FS17 attained an especially high REI value, much greater than any other site/year combination (Fig. 3). Examination of the detection records for this site revealed this anomaly to be caused by a short deployment of only 6 months (January – June) when it recorded a large number of detections. Coincidently, winter and spring are the two seasons during which transient species are most commonly visiting the sanctuary (Williams et al., 2019). As a result, the seasonal bias of a large amount of transmitter activity was automatically applied to the rest of the year through the deployment term (D_a/D_r) in the REI equation.

Examining the pairwise correlations between the REI and its individual terms at GRNMS revealed that almost all relationships between the REI and each of its component terms were all positive and significantly correlated (Fig. 4). The strongest relationship was between REI and detection days (DD_r/DD_a) (Fig. 4c). Weaker, but still significant, were the relationships between REI and proportions of species and individuals detected (S_r/S_a and T_r/T_a) (Fig. 4ab). Correlations between the complete REI and the REI calculated without each of its individual component terms demonstrates that the REI is robust to exclusion of any one component (Fig. 5). Similar to the pairwise correlation results, the REI without detection days (DD_r/DD_a) had the largest influence on the REI (Fig. 5c) compared to other components. Also of note, ranking of receiver locations at GRNMS using the overall REI versus each of its component measures revealed that the same sites were always ranked among the top five regardless of the measure used (REI, detections, individuals, species) but the specific rank-order of importance was not consistent (Table 1).

The role and influence of the deployment correction term (D_a/D_r) is also demonstrated in this analysis (Fig. 5d). Overall, the influence of correcting for receiver deployment time was minor, which is not surprising since most of the receivers were deployed for the entire year, which resulted in a value of 1 for their detection span (D_a/D_r = 365/365

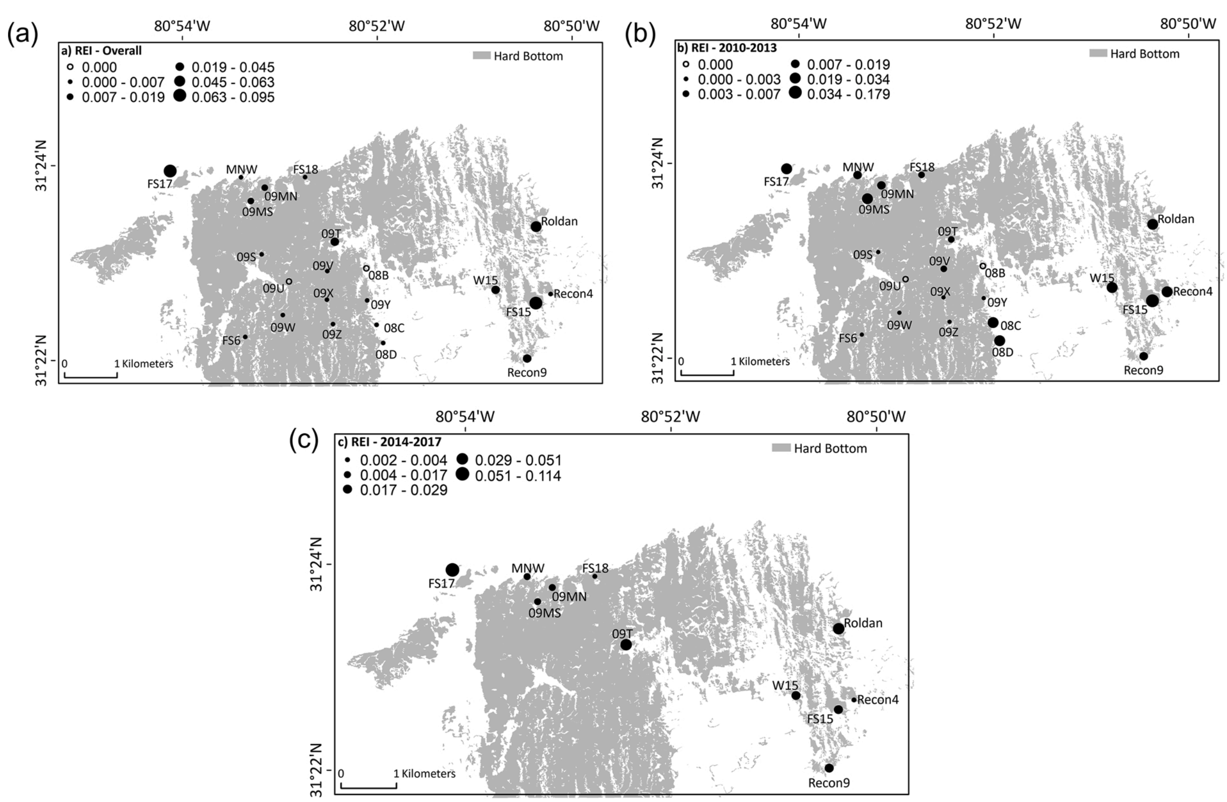

Fig. 2. a–c. Position of receivers in GRNMS and their corresponding REI values for (a) the entire time-series 2010-2017, (b) early years 2010-2013, and (c) later years 2014–2017.

Table 1
Station ranks at GRNMS based on REI overall, REI 2010–2013, REI 2014–2017, overall number of individuals, overall number of species, and overall detection days.

Station Name	Overall REI Rank	2010−2013 REI Rank	2014−2017 REI Rank	Num. Individuals Rank	Num. Species Rank	Num. Detection Days Rank
FS17	1	8	1	1	1	2
FS15	2	1	4	3	3	1
Roldan	3	4	3	4	2	3
09 T	4	13	2	2	5	4
W15	5	3	5	5	4	5
Recon9	6	10	6	7	8	6
09MS	7	2	7	6	7	7
09 MN	8	9	8	8	6	8
Recon4	9	5	10	10	10	9
MNW	10	11	9	9	9	11
FS18	11	12	11	11	11	10
08C	12	6	Not deployed	12	13	13
08D	13	7	Not deployed	13	14	12
09V	14	14	Not deployed	14	12	15
09Y	15	15	Not deployed	15	16	16
09X	16	16	Not deployed	17	15	14
09 W	17	17	Not deployed	16	17	17
FS6	18	18	Not deployed	19	19	19
09Z	19	19	Not deployed	18	18	18
09S	20	20	Not deployed	20	20	20
08B	22 (tie)	22 (tie)	Not deployed	22 (tie)	22 (tie)	22 (tie)
09U	22 (tie)	22 (tie)	Not deployed	22 (tie)	22 (tie)	22 (tie)

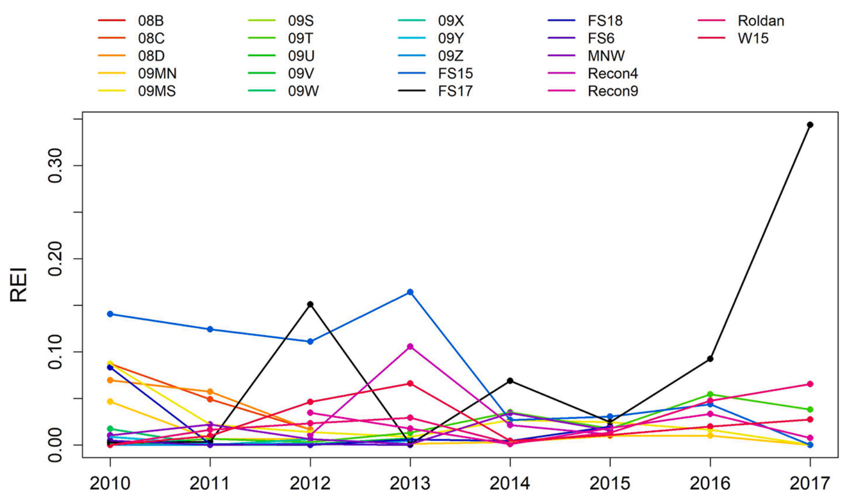

Fig. 3. REI at each receiver location in GRNMS on an annual basis.

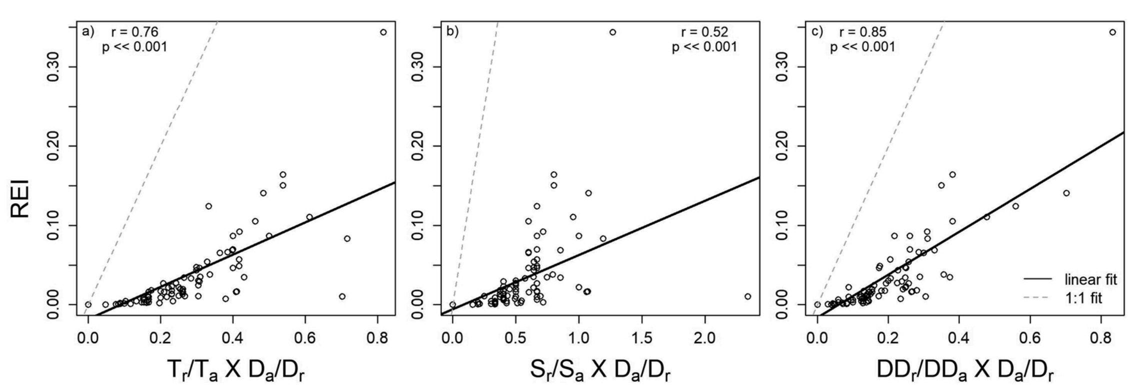

Fig. 4. a–c: Correlations between REI and (a) $T_r/T_a{*}D_a/D_r$, (b) $S_r/S_a{*}D_a/D_r$, and (c) $DD_r/DD_a{*}D_a/D_r$ at GRNMS.

= 1) and therefore a 1:1 relationship between the full REI and REI calculated without the time-correction term. Had there been a greater range in deployment span among receivers this outcome may have been different. Receivers deployed for the full year are represented in Fig. 5d as a straight line of points. Unlike calculation without the other terms, differences only occurred above the 1:1 line of agreement since D_a/D_r can only have values of 1 or greater and therefore REI can only increase when a receiver is not deployed for the entire timespan of the array. This is clearly evident in 2017 at FS17 in GRNMS, the point farthest at the top/right-hand side of the Fig. 5a–d.

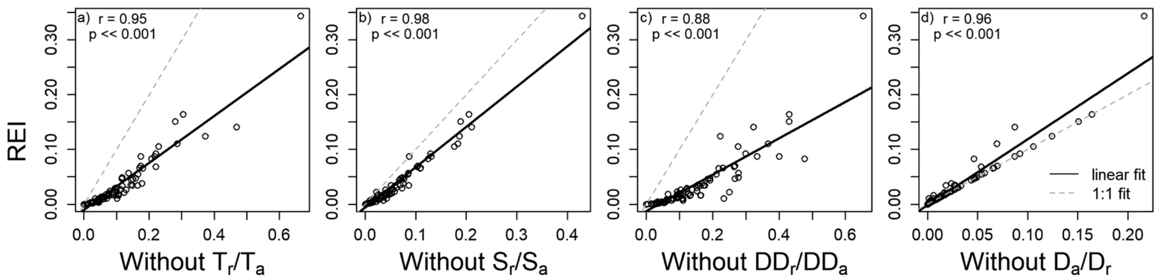

Fig. 5. a–d: Correlations between REI and the REI calculated successively without components of equation: (a) without T_r/T_a, (b) without S_r/S_a, (c) without DD_r/DD_a, and (d) without D_a/D_r at GRNMS.

Array performance at GRNMS was analyzed compared to *a priori* benchmarks and plotted as cumulative percentage of detections, species, and individuals against rank ordered REI to determine how many receivers may be necessary to maintain to achieve a target percentage of observations (Fig. 6a–c). For example, to detect at least 75 % of the individuals detected by the entire array, the top six receiver locations would be needed for the early years of the array but only the top three receiver locations would be needed in the later years of the array. Importantly, these are not the same locations in both time periods since REI ranks changed in the two time periods (Table 1). Detection of the same threshold (75 %) of all the species or detections in the array could be accomplished with the same number of receivers, however, again the particular receivers involved differed between the two time periods. Analogous figures for the Florida array can be found in Ellis et al. (2019).

Multivariate analyses were used to determine if receivers with similar REI values were detecting similar fish communities within both arrays. The nMDS ordinations of fish species assemblages in GRNMS (Fig. 7a–b) and west Florida (Fig. 8a–b) illustrate these differences. In the GRNMS plots, each point denotes a particular location/year combination, whereas in the Florida plots each point denotes a particular site across both years (2014–15) combined. Distances between points indicate the relative similarity in their fish assemblage, so points closer

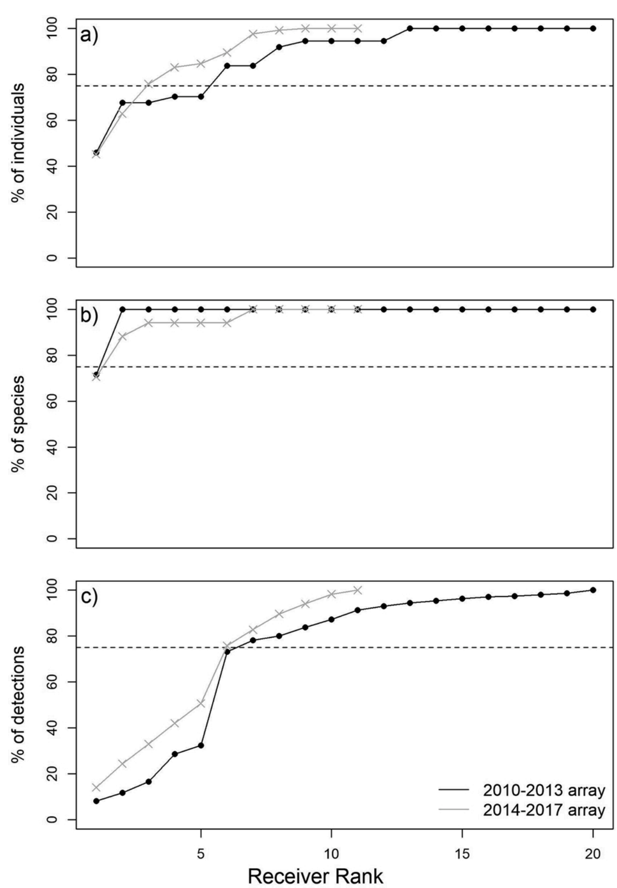

Fig. 6. a–c. Cumulative detection plots for GRNMS by rank ordered REI from the early versus later array configurations. Receivers with no detections (REI = 0, n = 2) are not included (08B and 09U 2010-2013 array).

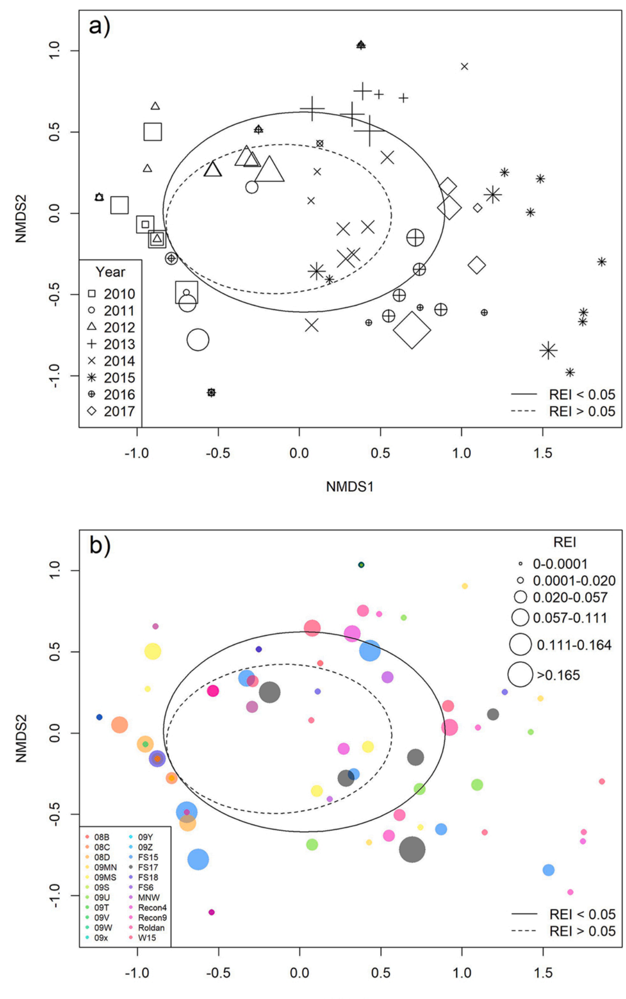

Fig. 7. a,b. nMDS plots of all the site/year combinations in the GRNMS array. Factor coding denotes (a) year, and (b) station, with symbol size in both plots scaled to REI value. Stress = 0.14. Ellipses represent the standard deviation of each group centroid (high REI vs low REI). Station/year combinations with REI = 0 (n = 18) are missing from these figures since they had no detections for any species and therefore could not be plotted based on dissimilarity of community composition (Stations 08B (2010, 2011, 2012), 09S (2010, 2012), 09 T (2010), 09U (2010), 09 W (2011, 2012), 09X (2011), 09Z (2010, 2011), FS15 (2017), FS18 (2012), FS6 (2011, 2013), Roldan (2010), W15 (2010)).

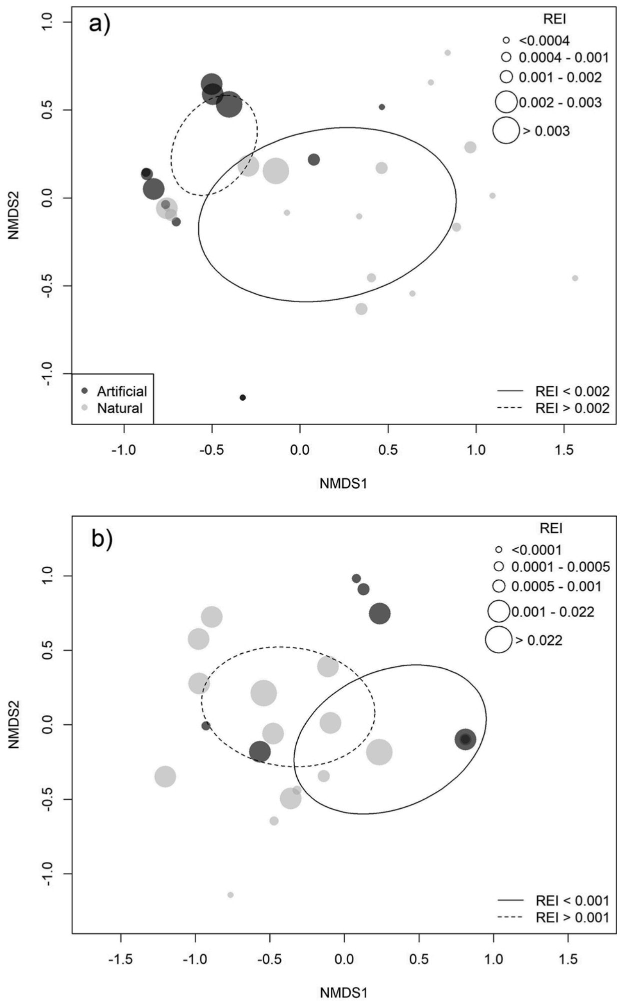

Fig. 8. a b. nMDS plot of receiver locations deployed in the Florida array from 2014-15 for all species detected (a) and for only non-target species (b). Symbol size is scaled to REI value. Colors are used to depict artificial (light grey) versus natural (dark grey) reefs. Final stress for all species = 0.125; final stress for non-target species = 0.07. Ellipses represent the standard deviation of each group centroid (high REI vs low REI). Due to the low number of non-target tags detected at nine sites, these sites reduced to a single point in NMDS space located at (0.81, -0.10).

together have relatively greater similarity in their assemblage than those farther apart. Comparing communities among years (Fig. 7a) versus locations (Fig. 7b) at GRNMS, it is clear that the groupings were driven primarily by year, where different sites spread throughout GRNMS but within the same year detected similar fish communities (e.g. the triangles in 7a represent 2012 data at all the sites and are plotting near each other). Likewise, there was significant turnover in the fish community detected at each individual location from year to year as exemplified by the widely spread grey dots in 7b that represent the different fish communities detected at site FS17 across years. Additionally for GRNMS, we determined if fish assemblages were similar across the years at the same site or if assemblages were similar based on location. The ANOSIM analysis comparing sites in the GRNMS array with high versus low REI values did not show differences in fish assemblages between these groups ($p = 0.76$, $R = -0.03$; Fig. 7). In contrast, ANOSIM results for the west Florida array suggested that sites with high versus low REI may represent slightly different fish communities ($p = 0.04$, $R = 0.17$) when all fish were included in the analysis (Fig. 8a). When only non-target fish were considered, ANOSIM results suggested stronger dissimilarities between fish communities with high versus low REI values ($p = 0.001$, $R = 0.301$; Fig. 8b). Furthermore, ANOSIM suggested differences between artificial and natural reef sites in terms of their REI values ($p = 0.02$, $R = 0.15$) when all fish were included. When only non-target fish were included, ANOSIM results did not support differences in fish communities between artificial and natural reef sites ($p = 0.24$, $R = 0.03$).

4. Discussion

Following the conception of any new index or analytical method, it is important to test its application and performance in a range of settings using a variety of datasets (Macdonald and Green, 1983; Liao et al., 2001; Hart et al., 2002). Using a long-term 8-year data set of acoustic telemetry detections from GRNMS, we evaluated the performance of a new composite index, the REI, by comparing the complete index to its constituent parts. We found that the REI is a robust index and that no single component had an overwhelming influence on the composite value. We were also interested in how multivariate community data aligned with the REI values and found that including them was an important addition to understanding the performance of arrays across space and time.

Analysis of the multiyear dataset from GRNMS showed that REI values varied through time at the same receiver location. Depending on the time-period that was analyzed, different conclusions could be drawn regarding which receivers were most important. For example, sites ranked 8th and 13th in importance during the early years of the array were ranked 1st and 2nd in importance in the later years of the array. These later years best encompass the ever-increasing diversity of tagged animals (Hussey et al., 2015; Williams et al., 2019), and therefore may be the better sites to maintain if the goal is to monitor individuals currently at large. In contrast, if there were particular species of interest more prevalent in early earlier years, higher ranking sites in those years may be more useful to maintain. It is also possible that consistency in receiver efficiency among years may be a more valuable trait than a high, but variable REI. Variable interannual efficiency may be due to an ephemeral resource (e.g., bloom of a food item), whereas stable efficiency may represent a more permanent hub of activity (e.g., reef or rock outcrop). Parsing array data annually as was demonstrated here, or even seasonally as discussed below, and evaluating the change in REI through time is advisable to understand temporal aspects of receiver efficiency.

The REI corrects for differences in deployment time when comparing among receivers by assuming that detection rates are consistent across the timespan of the array. However, this may not always be justified. Interpreting the REI in cases where the correction term (D_a/D_r) is large or there is a disparity in the seasons in which receivers are deployed (e.g. summer is missing at location A, winter is missing at B) warrants additional scrutiny. This is exemplified in the GRNMS data by site FS17 which attained an unusually high REI value in 2017 due to the preponderance of seasonal visitors during the limited time that the receiver was deployed. Transient and migratory species can have an especially strong seasonal bias in their presence at GRNMS. For example, White sharks (*Carcharodon carcharias*; n = 22) and Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*; n = 37) were detected almost exclusively in winter and spring, whereas Bull sharks (*Carcharhinus leucas*; n = 17) were detected primarily during summer and fall months (Stein et al., 2004; Skomal et al., 2017; Williams et al., 2019). In this case, the high REI value for FS17 in 2017 caused us to review potential bias in array deployment and revealed an interesting seasonal pattern of movement through the GRNMS. Likewise, researchers should be cautious in cases where there is a seasonal bias in either receiver deployment or fish presence and should mindfully interpret those effects on the REI.

A related consideration regarding temporal bias is the potential value of separating REI calculations for transient species versus resident species which may have very different detection patterns (Magurran and Henderson, 2003; Kendall et al., 2017). Transient species, by definition, are less likely to spend a long time in an array, will compile fewer detections, and are more likely to be detected at multiple receiver sites or periodically leave the array altogether. For example, massive schools of black tip sharks (*Carcharhinus limbatus*) undertake seasonal migrations along the southeastern USA that can bring them through GRNMS twice a year, but they move through the sanctuary in a single day (Kajiura and Tellman, 2016; Williams et al., 2019). In contrast, resident species are generally more sedentary, less mobile, and more site-attached, and will tend to be detected at fewer receivers but with many more detections. Some species exhibit very strong site fidelity, infrequently moving beyond the detection range of nearby receivers (Popple and Hunte, 2005; Farmer and Ault, 2011; Garica et al. 2014; Auster et al. (2020)). The west Florida array was designed primarily to assess site fidelity of two relatively sedentary species, Goliath Grouper and Gag (Collins et al., 2015), and their influence on REI values was evident when examined spatially (see Ellis et al., 2019). Similarly, species with day/night feeding migrations can often repeatedly visit the same resting sites, transit pathways, and foraging areas (Marshall et al. 2011, Kendall et al., 2017). In the case of resident species, it is additionally important to consider the location of tagging and its proximity to receivers. Locations with less transmitter activity and corresponding low REI scores may simply not have been near tagging/release sites, but may be just as important as fish habitat. It is worth considering how these biases may influence the perception of receiver importance when using the REI.

The results from GRNMS presented here also demonstrate just how influential spatial position of a receiver can be and, importantly, how location may interact with time. In general, we found that receivers along the edges of the hard bottom habitat at GRNMS tended to have the highest REI values. It is unknown whether these sites have some attraction to transient species as the first hardbottom encountered during their movements. It is also possible that detection range is simply higher at these sites which are often nearby large, flat sand patches which are more conducive to transmitter detection. Despite this, edge sites physically close together, even <300 m apart, often had very different REI values. Furthermore, REI values at the same site varied through time and these temporal differences were sometimes far greater than the differences among sites within the same year. In west Florida, where we did not have a long time series to evaluate, REI values nevertheless varied at the same site depending on the species group considered (e.g. resident versus transient). These patterns exemplify how the complex interaction between the increase in tagged animals over time, the specific life histories and habitat requirements of these species, and the seasonal and habitat-specific movement patterns unique to each species combine to complicate the analysis of acoustic detection data.

As a composite measure, the REI was designed to incorporate multiple aspects of acoustic telemetry detection data into a single value (i.e. number of detections, individuals, and species). We found that these elements can be highly correlated, which is not surprising because more species means more individuals and therefore usually more detections. Similarly, this redundancy was the topic of some early criticism of the IRI in gut contents studies where it was shown in an example dataset that all components of that index loaded heavily on the first axis of a principle component analysis and were therefore highly correlated (Macdonald and Green, 1983). Such results questioned the need to combine multiple measures of diet into one index if a single measure described most of the information just as well. One rationale for not using multiple measures in composite metrics for diet studies was the combined burden of both counting and weighing half-digested or partial prey items. This is, however, not of concern in telemetry studies where all the necessary variables are downloaded electronically in a tabular format that can be easily manipulated with statistical software. Each of these variables can be biased in different ways as noted in the introduction, thus the use of composite metrics prevents any bias present in one component of the equation from skewing the perception of overall receiver importance. This is demonstrated in the ranking of receiver locations at GRNMS using the overall REI versus each of its component measures. The same sites were always ranked among the top five regardless of the measure used (REI, detections, individuals, species) but the specific rank-order of importance was not consistent as the different biases in each component were emphasized.

It is important to recognize however, that even though ranks may change, all of these top five receivers may have similar value. Values close together get separate ranks, but in practice, there may be little difference between them. Stations FS17, FS15, and Roldan are good examples, where FS17 is technically ranked first, but the actual REI values of the others aren't meaningfully far behind. At the other extreme, sites with adjacent ranks may actually be quite different when there is a large jump in values. In some cases, it may be a better approach to consider receivers of similar value within categories (rather than ranks), all members of which are equally suitable to accomplishing an objective. As with the IRI, different conclusions could be drawn depending on which component was being used (Hart et al., 2002). For example, if setting targets for cumulative transmitter activity were a goal (e.g. detect 75 % of all individuals or species in the array), both the receivers chosen and how many are needed to accomplish the target could change depending on the metric used and the time period considered. Comparing both the REI and its component measures across multiple time-periods offers the most informative approach for identifying important receiver sites.

One aspect of detection data that the REI was not designed to investigate was species assemblage composition. Sites with similar REI values will not necessarily detect the same fish community. This is demonstrated by the nMDS results for GRNMS where we found that receiver deployments with similar fish assemblages did not have similar REI scores. In fact, the similarity of assemblages varied more across years rather than by location within GRNMS. We suspect that fish assemblages detected at GRNMS differed in part due to the increased number of tags at large, reflective of the general expansion of acoustic telemetry both in the region and worldwide (Hussey et al., 2015; Williams et al., 2019). These changes in species assemblage were evident at all sites, which may have been due to the relative uniformity in habitats found there. The bottom consists of just three main substrate types: sand, flat hard bottom, and rocky ledges (Kendall et al., 2005), and although resident fish communities differ among ledges of various sizes (Kendall et al., 2008, 2009), the ledges are all <3 m tall. Had there been a greater variety of reef types available, the transient assemblage may have shown more specialization among habitats. Such a pattern was evident in the west Florida array, which included both natural hardbottom ledges and high relief artificial reefs, and where we found a significant effect of bottom type on assemblages. However, the effect of habitat type in west Florida was only significant when all species were considered. Like GRNMS, we found no effect of habitat type in the west Florida array when considering just the transient species. This suggests that high site fidelity in the two target grouper species, which were primarily tagged at high relief artificial habitats (Goliath Grouper) and hardbottom ledges (Gag), drove differences in habitat type when all species were considered. Overall, these results indicate that coupling REI with community-based analysis are integral to disentangling those aspects of receiver efficiency that relate to which species and habitats are responsible for overall detection patterns.

Other useful tools exist that could be used to understand the importance of each receiver in an array. For example, Network Analysis has been recently gaining appeal in telemetry studies (see review by Jacoby and Freeman, 2016). This more complex analyses technique can reveal, among other things, which groups of receivers are visited the most, which pathways connect receivers in what directions, which fish communities are responsible for those patterns, and which receiver locations, if lost or removed, would cause the greatest disruption in understanding fish movements within the array (Finn et al., 2014; Kendall et al., 2017).

However, none of these analytical approaches is a replacement for certain common-sense decisions and the highest REI isn't always the 'best' site. For example, monitoring MPA borders often requires gates or linear arrays along their boundaries (Garcia et al., 2014; Kendall et al., 2017). The REI can reveal which part of the border receives most of the activity and may be the most important site to maintain, but the entire border may still require monitoring. There can also be situations wherein it is important to identify locations that are demonstrably less used by fish, such as when seeking to minimize impacts from disturbance activities (e.g. dredge spoil placement, cable laying, sand mining). In such cases, sites with the lowest REI may be attractive candidates. Of course, if the goal is to maximize species diversity or detection of a particularly important organism such as an endangered species, a more focused measure would be more appropriate.

The recommended time interval for evaluating receiver efficiency depends heavily upon individual research objectives, but there are key moments in the lifetime of an array that are good to consider. Because the REI is based on transmitter data, it is important to let enough time pass to collect sufficient detections that are representative of the research objectives. If seasonal changes are not of interest or concern, a minimum interval of a few months of data may suffice. In other cases, a complete annual cycle may be advisable to avoid seasonal bias. Another useful timeframe to evaluate receiver efficiency is after transmitter batteries have expired for an initial cohort of tagged fish. Receiver performance based on the first group of fish may be especially useful in improving the efficiency of receivers for tracking subsequent groups. Lastly, at the end of an array's primary lifespan, it may be desirable to examine receiver efficiency to inform future studies about best performing receiver settings, or for maintaining deployment of a smaller number of receivers in the retiring array to accomplish long term monitoring goals or maintain partnerships in telemetry networks.

Detection range of receivers is a critical aspect of their potential to record fish transmitters (Heupel et al., 2006; Kessel et al., 2013). Range can be influenced by many things including environmental conditions in the water and surrounding habitat, background noise, position of fish in the water column, and mooring height and tackle used to deploy the receivers (Clements et al., 2011; Mathies et al., 2014; Kendall et al., 2016; Selby et al., 2016). The REI inherently incorporates differences in receiver range into the process. Even though two receivers may in fact be visited by an identical number and diversity of fishes, the site with superior detection range will have a greater REI. This should be taken into consideration during interpretation. Adjustments to receiver height and deployment techniques that alter receiver range will likely alter the REI, as can seasonal changes in range such as thermocline development and biological noise.

5. Conclusions

It has become increasingly important to develop methods that quantify receiver importance as use of telemetry networks expands and array configurations are modified for optimal data collection to meet research objectives. As the use of acoustic telemetry continues to increase, we predict that tools like the REI will see increasing use by researchers looking to holistically evaluate the performance of their arrays. The REI is a composite measure designed to express the proportion of all transmitter activity in an array that occurs at each station. It is computationally simple to implement, intuitive to interpret, and easy to customize. In this study, we evaluate the REI using a multi-year dataset and explore the causes of fluctuations in the index over time. This has resulted in additional guidance that should be considered during its use and interpretation. For example, it may be desirable to include only relevant species groups (resident versus transient), time periods (seasonal, interannual), or parts of the equation (e.g. perhaps duration of stay is not important and therefore detections days can be left out). We also recommend that the REI be coupled with community assemblage analyses for each receiver, such as clustering or nMDS, as was done here. This combination can be helpful in revealing details about the species and communities that drive differences in REI values in ways that simply examining the REI alone does not. Such information can be used to determine which receivers are detecting similar communities and therefore potentially redundant information and which sites include unique or target assemblages, and therefore how best to deploy limited telemetry resources.

Author contributions

MK was the primary author. BW conducted analyses. RE conducted analyses and contributed to writing. AC, KR, and KF contributed data, conceptual guidance, and contributed to writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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