Ecological Indicators 123 (2021) 107310

Contents lists available at ScienceDirect

Ecological Indicators

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

# A multimetric nekton index for monitoring, managing and communicating ecosystem health status in an urbanized Gulf of Mexico estuary

Meagan N. Schrandt [a,*], Timothy C. MacDonald [a], Edward T. Sherwood [b], Marcus W. Beck [b]

[a] Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, 100 Eighth Avenue SE, St. Petersburg, FL 33701, United States
[b] Tampa Bay Estuary Program, 263 13th Ave. South, Suite 350, St. Petersburg, FL 33701, United States

ARTICLE INFO

*Keywords:*
Tampa Bay
Biological indicator
Fisheries
Red tide
Ecosystem health
Resilience

ABSTRACT

Biological assessments have been used for decades to determine ecological conditions in aquatic environments, yet they have not been extensively applied in estuaries that serve as transition zones between freshwater and marine environments. We present the development and validation of a nekton (fish and selected macro-invertebrate) index for annual monitoring of ecosystem health in Tampa Bay, Florida. We relied on long-term fisheries independent monitoring data of the early recruit and juvenile life history stages of nekton in Florida's inshore waters. A set of metrics that included measures of abundance, species diversity, trophic structure, and taxa of commercial or recreational importance were explored, and a subset was selected via statistical models. Reference conditions specific to each season and management section of the bay were established from the long-term dataset. The final Tampa Bay Nekton Index included five metrics: the total number of taxa, the number of benthic taxa, the number of recreational/commercial fishery taxa, the number of feeding guilds, and the Shannon-Weiner diversity index. Nekton index scores were calculated for each sample and averaged by bay management section and year and then a "stoplight" color-coding system, based on quantiles, was used to group index scores for communication and management. In general, Tampa Bay's nekton community appears to be resistant to large-scale changes in functional structure. The index was sensitive to a prolonged red tide event but eventually returned to preperturbation levels, indicating nekton community resilience. This index will be incorporated into monitoring and managing strategies of the local estuary program. Because this index was developed specifically for Tampa Bay and relies on bay-specific reference conditions, the index cannot be directly applied to other systems, but the methodology is transferrable so similar indices could be developed for other ecosystems with long-term monitoring data. Furthermore, using regional data, the index could be expanded/developed to assess health status *among* estuaries to inform decisions on prioritization of limited resources.

## 1. Introduction

The Oceans Act in North America and Australia, the Water Framework Directive in Europe, and the National Water Act in South Africa are some of several legislative directives worldwide that address the ecological quality and integrity of estuarine and coastal systems (Borja et al., 2008). Environmental policies in many countries include monitoring and managing estuaries (Karr, 1991; DWAF, 1998; European Community, 2000; Ferreira et al., 2007) and some specify using biological indicators for assessing ecological status (Ferreira et al., 2007). Multimetric biological indicators integrate many characteristics into a single scale that can be easily communicated to end users who include scientists, the public, managers, and legislators. National estuarine monitoring programs in the United States, Europe, and South Africa use biotic indices (Deegan et al., 1997; Bilkovic et al., 2005; Harrison and Whitfield, 2006; Uriarte and Borja, 2009) that could be combined with measures of ecosystem function (e.g., primary productivity, respiration; Woodward et al., 2012) or physicochemical indices (Borja et al., 2008) to provide a more comprehensive view of whole ecosystem health.

Since 1991, the Tampa Bay Estuary Program (TBEP) has been a key promoter of ecosystem health because it is responsible for monitoring, restoring, and protecting Tampa Bay, Florida (USA). The TBEP, one of 28 programs administered by the U.S. Environmental Protection Agency (USEPA) under the National Estuary Program, operates under a

* Corresponding author.
*E-mail addresses:* Meagan.Schrandt@MyFWC.com (M.N. Schrandt), Tim.MacDonald@MyFWC.com (T.C. MacDonald), esherwood@tbep.org (E.T. Sherwood), mbeck@tbep.org (M.W. Beck).

https://doi.org/10.1016/j.ecolind.2020.107310
Received 5 June 2020; Received in revised form 15 December 2020; Accepted 21 December 2020
Available online 20 January 2021

comprehensive management plan (Tampa Bay Estuary Program, 2017), which includes using environmental indicators to assess status and trends within the estuary and its watershed. The TBEP also considers human needs to support a strong economy because Tampa Bay is an urban, mixed-use estuary with active ports, land-based industries, commercial and recreational fisheries, and public recreation activities. Almost 70% of the watershed lands have been developed for urban/suburban, agriculture, and extractive/mining purposes (Southwest Florida Water Management District, 2011). Meanwhile, one in five jobs in the Tampa Bay watershed depends on a clean, healthy bay (Tampa Bay Regional Planning Council Economic Analysis Program, 2014). A combination of target- or threshold-based management strategies (water quality) and environmental indicators (benthic sediments, benthic biota, seagrass) to confer estuary health has been used to effectively monitor and guide management actions within this highly developed watershed.

Current management strategies in Tampa Bay have proven successful in restoring critical habitats lost due to human-induced eutrophication that had resulted in significant seagrass bed declines prior to the 1980's. Subsequent monitoring of water quality, reductions in nutrient loading into the watershed, and habitat restoration activities helped restore seagrass coverage to levels exceeding those in the 1950's (Greening et al., 2014; Sherwood et al., 2017). Water quality is monitored using water clarity indicators (e.g., chlorophyll-a and Secchi disk depths), and a "stoplight" color scheme (i.e., green, yellow, and red) was developed to guide management action (Janicki et al., 2000; Sherwood et al., 2017). In addition to a water quality indicator, benthic sediment quality (Karlen et al., 2015) and a Tampa Bay benthic biotic index (TBBI; Malloy et al., 2007) are currently used for ecosystem management purposes.

Fishing is one of the most popular recreational activities in the Tampa Bay area and a nekton (fish and selected macroinvertebrate) index has been an important but missing tool for communicating the status of this community to concerned stakeholders. Therefore, our objective was to develop a multimetric nekton index capable of tracking the annual response of nekton communities in Tampa Bay to environmental conditions. Ultimately, the Tampa Bay Nekton Index (TBNI) may be integrated with other indices to provide a more holistic approach to assessing, managing, and communicating ecosystem health of the Tampa Bay estuary.

## 2. Material and methods

### 2.1. Multimetric index overview

Procedures for developing multimetric biotic indices generally follow a common workflow. The process includes the development and selection of metrics, testing of potential metrics and refining as needed with new metrics, defining or determining reference conditions (e.g., unimpacted or least impacted sites, "best-available" conditions), validating selected metrics, and iterative monitoring of reference sites to recalibrate the index periodically. The following subsections describe the approach used for the development of a multimetric nekton index for the Tampa Bay estuary, closely following the approach developed by Hallett et al. (2012a, 2012b) for a multi-species index in the Swan Estuary in southwestern Australia where, as in Tampa Bay, pristine reference sites are absent or difficult to distinguish.

### 2.2. Nekton sampling

The Florida Fish and Wildlife Conservation Commission's (FWC) Fish and Wildlife Research Institute's (FWRI) Fisheries-Independent Monitoring (FIM) program has a long-term, statewide nekton monitoring dataset that was used for developing the TBNI. Although three gear types are used for year-round sampling of nekton communities, we will focus on the gear type with the longest consistent sampling protocol, which is a center-bag haul seine (21.3-m × 1.8-m with 3.2-mm nylon mesh). The seine is either pulled adjacent and parallel to the shoreline or > 5 m from the shoreline into the prevailing current and generally collects early recruits, juveniles, and smaller-bodied nekton. Seine sampling methodology is standardized (all seines are sampled for the same width and distance) so that sets sample 140 $m^2$ of bay bottom. Samples are collected in waters ≤ 1.5 m deep to ensure the net captures specimens as intended. For reference, the average depth of Tampa Bay is < 4 m, with most deeper areas confined to commercial shipping channels or dredging locations. All collected fish and selected invertebrates (e.g., swimming crabs [*Callinectes* spp., *Portunus* spp.], stone crabs [*Menippe* spp.], penaeid shrimp [*Farfantepenaeus* spp. and *Litopenaeus* spp.], and scallops [*Argopecten* spp.]) are identified to the lowest possible taxon (usually species), counted, and a subset is measured. Current protocols were established in 1998; hence, catch data from 1998 through 2015 were used to develop the TBNI. Since 2016, the TBNI has been applied to FIM catch data for validation and to provide annual updates for bay management.

FIM's nekton sampling is stratified into five bay areas that generally have similar biological and hydrological characteristics, and sampling is proportioned among bay areas based upon available habitat that can be effectively sampled. The TBEP expressed interest in an index for the bay proper, specifically the four major bay segments they have consistently used for bay management: Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay (Fig. 1). The TBEP bay segment delineations differ from the FIM sampling areas used for stratified random sampling, and the FIM areal coverage extends beyond the TBEP bay segments to include rivers and tidal tributaries (Fig. 1). Therefore, the FIM dataset (1998–2018) was a subset of only those samples collected within the four TBEP bay segments based on the samples' positions (latitude and longitude). A total of 5,212 seine samples (Table 1) were identified for index development (1998–2015). Seasonal variation in catches was expected, so each sample was assigned to a season, based on Tampa Bay's natural variation in surface water temperatures, measured at the time of nekton sampling (Winter = December–March, Spring = April–May, Summer = June–September, Fall = October–November).

### 2.3. Metric development and selection

#### 2.3.1. Functional ecological guilds

To develop a more generalized index (i.e., not an index based on specific taxa that may or may not be present in the system in the future), we focused on nekton functional roles in the estuary as opposed to individual species. This is a widespread practice for multimetric indices that began with the original index of biotic integrity (Karr, 1981). Hence, all fish and selected invertebrates captured in Tampa Bay were assigned to functional ecological guilds (e.g., Elliott et al., 2007; Potter et al., 2015) prior to calculation of potential metrics (see Appendix A for a full catch list by TBEP bay segment, accompanied by guild assignments, and Appendix B for further description of guild assignments). Three broad guild categories were considered: 1) habitat, reflecting the preferred water column positioning of the species, 2) estuarine use, reflecting how the species uses the Tampa Bay estuarine system (i.e., life history), and 3) feeding, reflecting the breadth of diet of the adults of each species. Guild assignment was based on information from published literature and FishBase, IUCN, and Smithsonian Institute webpages.

#### 2.3.2. Potential metrics

The overall goal was to combine multiple metrics to build an index that accounts for natural, small-scale spatiotemporal variability in estuarine nekton communities (i.e., community changes due to variations in nekton recruitment, development, and seasonal use of estuarine areas) while remaining sensitive to annual changes in ecosystem health, thus providing the ability for annual tracking of estuary nekton condition. A list of potential nekton metrics (Appendix B) was developed after reviewing literature of fish indices and consulting with scientists

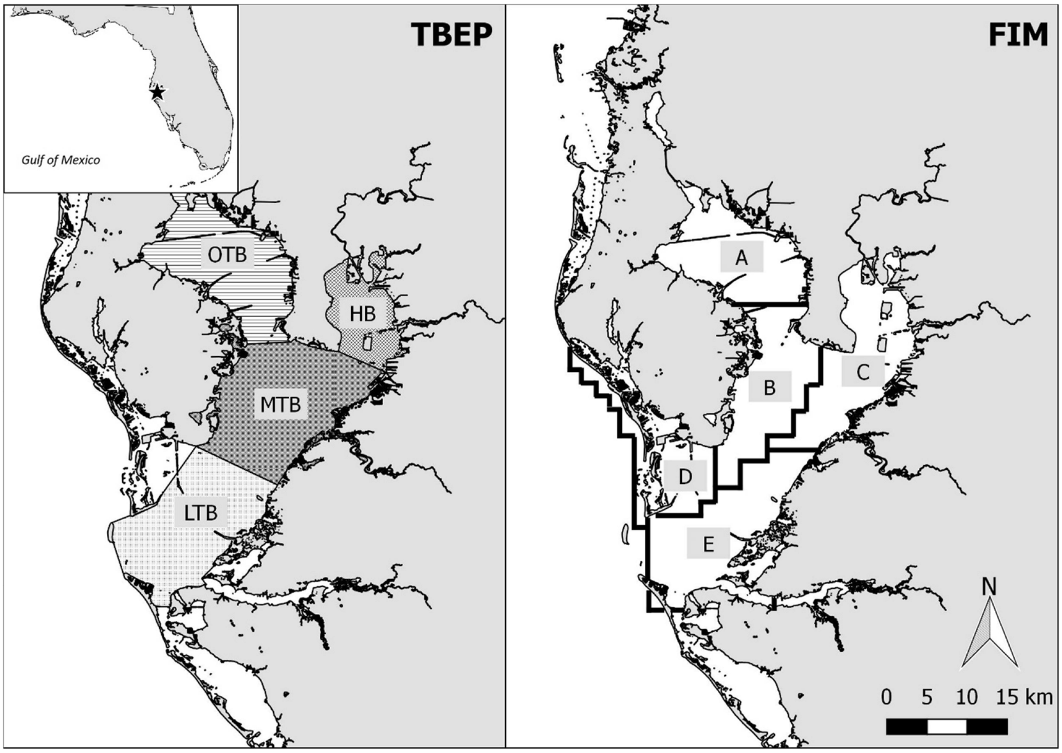


**Fig. 1.** Management zones of the Tampa Bay Estuary Program (TBEP; OTB = Old Tampa Bay, HB = Hillsborough Bay, MTB = Middle Tampa Bay, LTB = Lower Tampa Bay) for Tampa Bay, Florida (*Left*). Sampling zones for Florida Fish and Wildlife Research Institute's Fisheries-Independent Monitoring (FIM) program's monthly stratified random sampling design for Tampa Bay, Florida (*Right*).

familiar with the Tampa Bay estuary. The potential metrics spanned multiple community characteristics including species diversity, abundance, composition, trophic levels, life history and estuarine use, and specific focal species. Metrics relating to "selected taxa," recreationally and/or commercially important taxa (e.g., *Centropomus undecimalis*, *Callinectes sapidus*; designated by an "s" superscript in Appendix A), were also considered. When applicable, multiple variants of a metric were calculated and examined, e.g., the number of individuals, number of taxa, and proportion of total individuals.

Before evaluating and selecting specific metrics, several were excluded from further consideration because of lack of information (i.e., metrics with $< 35\%$ frequency of occurrence, a natural break in the distribution of frequencies) or high correlation (Pearson correlation $r \geq 0.95$) with other metrics. Additionally, feeding and habitat metrics were

**Table 1**
Number of seine samples collected from the four Tampa Bay Estuary Program bay segments during different seasons (Wi = winter, Sp = spring, Su = summer, Fa = fall). Samples from 1998 to 2015 (N = 5,212) were used to develop the small seine index and the index was then calculated for each year thereafter (2016–2018).

| Year | Old Tampa Bay (OTB) | | | | Hillsborough Bay (HB) | | | | Middle Tampa Bay (MTB) | | | | Lower Tampa Bay (LTB) | | | | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wi | Sp | Su | Fa | Wi | Sp | Su | Fa | Wi | Sp | Su | Fa | Wi | Sp | Su | Fa | |
| 1998 | 24 | 12 | 28 | 13 | 10 | 5 | 14 | 7 | 23 | 11 | 16 | 8 | 15 | 8 | 22 | 6 | *222* |
| 1999 | 24 | 12 | 24 | 15 | 14 | 7 | 14 | 8 | 24 | 11 | 20 | 7 | 13 | 9 | 16 | 10 | *228* |
| 2000 | 27 | 12 | 25 | 15 | 9 | 9 | 15 | 8 | 32 | 11 | 28 | 12 | 15 | 7 | 13 | 5 | *243* |
| 2001 | 29 | 13 | 29 | 13 | 16 | 5 | 14 | 8 | 17 | 15 | 25 | 10 | 15 | 4 | 14 | 8 | *235* |
| 2002 | 25 | 14 | 24 | 14 | 13 | 8 | 11 | 6 | 27 | 11 | 32 | 17 | 6 | 7 | 12 | 4 | *231* |
| 2003 | 27 | 11 | 26 | 14 | 18 | 9 | 14 | 9 | 20 | 14 | 27 | 11 | 10 | 5 | 11 | 3 | *229* |
| 2004 | 29 | 17 | 29 | 13 | 15 | 7 | 12 | 8 | 21 | 8 | 25 | 12 | 15 | 6 | 15 | 8 | *240* |
| 2005 | 34 | 20 | 36 | 19 | 25 | 11 | 26 | 11 | 32 | 12 | 29 | 13 | 19 | 11 | 18 | 9 | *325* |
| 2006 | 34 | 21 | 41 | 19 | 21 | 14 | 19 | 11 | 35 | 13 | 31 | 13 | 17 | 10 | 19 | 14 | *332* |
| 2007 | 38 | 16 | 39 | 16 | 25 | 11 | 26 | 12 | 24 | 18 | 26 | 18 | 21 | 7 | 22 | 7 | *326* |
| 2008 | 35 | 17 | 42 | 20 | 23 | 10 | 24 | 12 | 33 | 17 | 26 | 13 | 25 | 9 | 16 | 12 | *334* |
| 2009 | 35 | 18 | 36 | 20 | 22 | 15 | 21 | 10 | 34 | 15 | 32 | 15 | 18 | 7 | 17 | 10 | *325* |
| 2010 | 36 | 18 | 38 | 19 | 29 | 12 | 29 | 12 | 26 | 16 | 27 | 14 | 17 | 10 | 20 | 10 | *333* |
| 2011 | 39 | 20 | 38 | 20 | 26 | 12 | 21 | 11 | 28 | 13 | 36 | 14 | 17 | 8 | 15 | 9 | *327* |
| 2012 | 38 | 18 | 35 | 21 | 23 | 9 | 25 | 12 | 31 | 18 | 31 | 14 | 13 | 6 | 15 | 6 | *315* |
| 2013 | 36 | 16 | 38 | 15 | 20 | 8 | 21 | 12 | 35 | 22 | 35 | 18 | 16 | 6 | 16 | 8 | *322* |
| 2014 | 35 | 21 | 39 | 19 | 26 | 15 | 21 | 13 | 32 | 12 | 32 | 13 | 13 | 8 | 10 | 8 | *317* |
| 2015 | 41 | 18 | 40 | 17 | 25 | 11 | 27 | 12 | 28 | 15 | 20 | 16 | 15 | 11 | 20 | 12 | *328* |
| 2016 | 36 | 20 | 38 | 20 | 21 | 14 | 23 | 11 | 35 | 13 | 31 | 17 | 20 | 10 | 11 | 9 | *329* |
| 2017 | 39 | 18 | 35 | 19 | 20 | 13 | 28 | 11 | 32 | 15 | 28 | 16 | 17 | 5 | 18 | 11 | *325* |
| 2018 | 39 | 22 | 40 | 19 | 24 | 15 | 21 | 12 | 29 | 8 | 32 | 13 | 15 | 7 | 13 | 7 | *316* |
| *Total:* | *700* | *354* | *720* | *360* | *425* | *220* | *426* | *216* | *598* | *288* | *589* | *284* | *332* | *161* | *333* | *176* | *6182* |

condensed to reduce complexity. This resulted in a refined set of 27 potential metrics (Table 2; metric aliases are also presented). Each metric was then calculated for each sample and analyzed with either SAS software (v. 7.1; SAS Institute Inc., Cary, NC, USA) or PRIMER v7 with PERMANOVA + software (PRIMER-e, Auckland, New Zealand).

#### 2.3.3. Data preparation

Each metric was first transformed, where necessary, to stabilize its variance across different bay segment × season × year combinations so that general linear models could be applied. Appropriate transformations, following Box-Cox transformations (Clarke et al., 2014), were determined by examining the slope of the relationship between $\log_e$(mean) and $\log_e$(SD), where SD is the standard deviation for the various combinations. Depending on the extent of the slope, a transformation of either none, square root, fourth root, or log(0.01 + x) was applied to either the × value or its complement (1–x) for proportions (Table 2). Pairwise scatterplots and associated Pearson correlation coefficients were assessed to determine the degree to which metrics were correlated (i.e., redundancy among metrics). Highly correlated metrics ($r > 0.95$) were assessed and the more specific of the correlated metrics (i.e., those with additional information requirements like spawning location or diet) were removed from further analyses (e.g., estuarine obligate taxa [*TaxaObl*] and trophic specialist taxa [*TaxaTS*] were highly correlated with *TaxaNum* and therefore eliminated from consideration).

Multiple metrics differed in relative variability within bay segment × season × year combinations so all values were variability weighted after transformation (Clarke et al., 2014). Variability weighting was achieved by dividing each metric value by its average standard deviation, calculated as the mean of the standard deviations for each combination of bay segment × season × year. This relatively up-weighted metrics with comparatively consistent values across replicate samples and simultaneously down-weighted highly variable or erratic metrics (e.g., metrics affected by schooling species with highly variable catches depending on whether a school is sampled). To focus on interannual differences in fish metrics while accounting for differences among bay segments and seasons and their interactions that have an effect on fish community composition, all samples were moved to a common centroid in Euclidean space. We did this by calculating the mean of all samples for each treated metric (across all years) in each bay segment × season combination. Then we subtracted the appropriate bay segment × season mean from each sample value. This produced a dataset of the main interannual effects and residual differences under the reduced model, hereafter referred to as the metric residuals. Metric residuals were used in the metric selection process while metric values were used for index calculations.

#### 2.3.4. Model matrix

In PRIMER v7, the metric residuals were averaged by bay segment × year × month combinations (these are considered replicates in the FIM sampling design), and a Euclidean distance matrix was constructed between all pairs of sampling years for 1998 through 2015. The Euclidean distance matrix was then used to create a model matrix, wherein comparisons within a year were given a distance = 0 and those from different years were given a distance = 1.

#### 2.3.5. Metric selection

To select the subset of metrics that best modelled the interannual differences (0–1 model matrix), we used a linear model and a fully nonparametric, nonlinear approach, each with a stepwise forward selection/backward elimination algorithm. Distance-based linear modelling (DISTLM in PRIMER; McArdle and Anderson, 2001) was applied first with selection criteria to select the best model based on the Akaike Information Criteria (AIC). We applied the DISTLM routine with 9 permutations, beginning with 1–15 starting variables and running 10 restarts. With 27 potential metrics and millions of possible combinations, we opted to keep the number of permutations low and the selection process more liberal (originally to include any selected metric in the TBNI). The second model used for metric selection was the BVSTEP routine in PRIMER (part of the BIO-ENV, "biology-environment" procedure), which searched for the subset of metrics whose pattern of rank order resemblances best matched those of the model matrix, indicated

**Table 2**
List of reduced metrics, along with aliases and transformations, included in the metric-selection models (DISTLM = Distance-based linear modelling, BVSTEP = Stepwise routine after Clarke and Ainsworth, 1993). Direction refers to the predicted direction of the metric in response to environmental degradation.

| Metric for Small Seine Models | Alias | Transformation | Selected by Model? | | Direction |
|---|---|---|---|---|---|
| | | | DISTLM | BVSTEP | |
| Pielou's Evenness (J) | *Pielou* | none | | | — |
| Shannon Diversity (H) | *Shannon* | none | ✓ | | — |
| *Lagodon rhomboides* abundance | *Num_LR* | log(0.01 + x) | ✓ | ✓ | — |
| Number of benthic individuals | *NumBenthic* | log(0.01 + x) | | | — |
| Number of estuarine spawning individuals | *NumES* | log(0.01 + x) | | ✓ | — |
| Number of trophic guilds | *NumGuilds* | square root | ✓ | | — |
| Number of individuals | *NumIndiv* | log(0.01 + x) | ✓ | | + |
| Number of marine spawning individuals | *NumMS* | log(0.01 + x) | | | — |
| Number of pelagic individuals | *NumPelagic* | log(0.01 + x) | | | + |
| Number of individuals of 'selected species' | *NumSelect* | log(0.01 + x) | ✓ | | — |
| Number of trophic generalist individuals | *NumTG* | log(0.01 + x) | ✓ | | + |
| Number of trophic specialist individuals | *NumTS* | log(0.01 + x) | | | — |
| Proportion of individuals that are benthic | *PropBenthic* | log(0.01+(1-x)) | | | — |
| Proportion of individuals that are estuarine spawners | *PropES* | log(0.01+(1-x)) | | | — |
| Proportion of individuals that are marine spawners | *PropMS* | log(0.01+(1-x)) | | | — |
| Proportion of individuals that are estuarine obligates | *PropObl* | log(0.01+(1-x)) | | | — |
| Proportion of individuals that are pelagic | *PropPelagic* | log(0.01+(1-x)) | | | + |
| Proportion of individuals that are 'selected species' | *PropSelect* | log(0.01+(1-x)) | | | — |
| Proportion of individuals that are trophic generalists | *PropTG* | log(0.01+(1-x)) | | | + |
| Proportion of individuals that are trophic specialists | *PropTS* | log(0.01+(1-x)) | | | — |
| Number of benthic taxa | *TaxaBenthic* | square root | ✓ | | — |
| Number of estuarine spawning taxa | *TaxaES* | square root | | | — |
| Number of marine spawning taxa | *TaxaMS* | square root | | | — |
| Species richness | *TaxaNum* | square root | ✓ | | — |
| Number of pelagic taxa | *TaxaPelagic* | square root | | | + |
| Number of 'selected species' | *TaxaSelect* | square root | ✓ | ✓ | — |
| Number of trophic generalist taxa | *TaxaTG* | square root | | | + |

by the Spearman's rank "matrix correlation" coefficient (Clark and Ainsworth, 1993; Clark et al., 2008). The best model was determined as that with the greatest correlation with the response (model matrix) data. We applied the BVSTEP routine starting with different, randomly selected subsets of metrics (1–6 metrics). Metrics were selected for inclusion in the TBNI if they were identified by either of the two models but since this approach might retain more metrics than necessary, retained metrics would be assessed further with index diagnostics (section 2.7) to determine whether metrics could be removed from the TBNI.

### 2.4. Reference conditions

Reference data to describe a prehuman-impact period were not available, so the standardized, long-term nekton monitoring data for Tampa Bay (1998–2015) were used to establish "best available" reference conditions. The previously calculated metric values (selected metrics only) for each sample were used to determine reference conditions. Prior to analysis, each metric was classified as having either positive or negative directionality (an *a priori* hypothesis), depending on whether the metric was predicted to increase or decrease in response to ecological degradation (Table 2). Our *a priori* hypotheses were informed from both expert knowledge of the fish fauna of Tampa Bay and previous work by Hallett (2010) since we tested many of the same metrics. Species diversity, composition, and abundance metrics were generally considered negative metrics as they tend to decline in other indices of biotic integrity. The exceptions for Tampa Bay were the metrics pertaining to small pelagic individuals, where we hypothesized those to be positive metrics as the system may have increases in small pelagic, planktivorous species (e.g., *Anchoa* spp.) with non-pristine ecological conditions. By extension of this principle, we then hypothesized the total number of individuals could also be positive because the increase in the number of small pelagic individuals may outweigh the decrease in other taxa. Introduced species, generalist, and detritivore trophic metrics were considered positive metrics since environmental stress can favor taxa with generalist feeding preferences (Hughes et al., 1998). Metric percentiles were then used to establish reference conditions to avoid the influence of extreme outliers (Gibson et al., 2000) and because management entities seek to improve conditions within realistic targets. Reference conditions were calculated for each bay segment × season combination to reduce the potential for bay segment and season differences in nekton community assemblages to impact reference conditions. The 95th and 5th percentiles of each bay segment × season combination were calculated; the upper (95th percentile) was considered the best available reference condition for negative metrics and the lower (5th percentile) was considered the best available reference condition for positive metrics. Therefore, reference conditions for negative metrics are generally larger numbers and reference conditions for positive metrics are smaller numbers (see Appendix C for a conceptual diagram).

$$Positive\ Metric\ Score = \left(1 - \frac{(Observed\ Metric\ value - Lower\ threshold)}{(Upper\ threshold - Lower\ threshold)}\right) \times 10 \tag{2}$$

### 2.5. Index score calculation

Metric scores were calculated for each sample as in Hallett et al. (2012b), using the appropriate bay segment × season reference condition, and were scaled continuously from 0 to 10. For cases where no nekton was captured in a sample, all metric scores were zero. If metric values exceeded the upper threshold or were less than the lower threshold (i.e., outliers), the sample received a metric score of 10 or 0, respectively. All other scores (values between the thresholds) were calculated by either Equation (1) for negative metrics or Equation (2) for positive metrics (Hallett et al., 2012b), below.

$$Negative\ Metric\ Score = \frac{(Observed\ Metric\ value - Lower\ threshold)}{(Upper\ threshold - Lower\ threshold)} \times 10 \tag{1}$$

Index scores for each sample were obtained by summing the scores of the selected metrics, dividing by the number of metrics in the index, and multiplying by 10 to yield a final score ranging from 0 to 100. Yearly scores for Tampa Bay were calculated by averaging all scores for the year. Bay segment-specific yearly scores were calculated by averaging scores by bay segment and year. To keep communication and reporting consistent with other Tampa Bay ecosystem indices, a "stoplight" (green = Stay the Course; yellow = Caution Alert; red = On Alert) color-coding system (Janicki et al., 2000) was applied to communicate nekton health status and guide management decisions (Karlen et al., 2015; Sherwood et al., 2017). Management response delineations depended on results from model selection and score calculation, and the specific thresholds for color assignment can be found in section 3.3, below.

### 2.6. Validating index sensitivity and reliability

Since we used an objective, statistical model approach to select metrics and applied best available reference conditions, a test of index sensitivity was needed to examine the ecological relevance of the index. We did this by assessing the TBNI in response to a known red tide (*Karenia brevis* algae bloom) event. From January 2005 through February 2006, a significant red tide affected the Tampa Bay estuary and nearshore coastal waters (Flaherty and Landsberg, 2011). More than 500 square miles of coastal waters off southwest Florida were affected, with documented kills of fish, manatees, dolphins, and sea turtles (Flaherty and Landsberg, 2011), and changes in the benthic invertebrate and demersal fish communities at artificial reef sites 19 to 25 km west of Tampa Bay (Dupont et al., 2010). Monthly nekton sampling was ongoing in Tampa Bay through this event, so index scores were compared before (<2005), during (2005), and after (>2005) this extensive red tide event to evaluate index sensitivity.

To assess the consistency and repeatability of index assessments (i.e., index reliability), we examined mean monthly index scores and their accompanying "stoplight" colors. We were looking for predictable seasonal patterns and greater variation in monthly index scores than in yearly index scores. Additionally, in January 2010, south Florida experienced lower than average water temperatures, causing widespread mortality of subadult/adult *Centropomus undecimalis* (Stevens et al., 2016), a common piscivore in Tampa Bay and an important recreational fishery species. Because this cold event had a relatively short temporal presence and directly impacted a single species, we would not expect this event to change the overall health status of the estuary for the year. Rather, we would expect to find winter index scores outside the previous range of winter TBNI scores.

### 2.7. Index diagnostics

To further refine the index and ensure that it was parsimonious (e.g., sensitive, reliable, and not overparameterized), we used two diagnostic techniques. First, we tested Pearson correlations between metric values and TBNI scores to assess whether metrics displayed expected relationships with the TBNI. For example, we hypothesized that the number of taxa would be positively correlated with the TBNI. Second, we performed a Principal Components Analysis (PCA) on the metric scores to evaluate consistency among metrics. If all metrics had eigenvectors in the same direction (positive or negative) on the first principal component, all metrics would be consistent in their role in the index. Furthermore, the relative magnitude of the eigenvectors would be valuable for determining which metrics were relatively more informative for the nekton index. Metrics with low correlation ($r < 0.7$) to index scores and small eigenvectors were subsequently removed from the index to avoid overparameterization. Index scores and "stoplight" color assignments were then recalculated. To assess the agreement between the original index and the reduced-metrics index, we calculated the Spearman's *rho* correlation coefficient between scores calculated from each index. High correlation coefficients suggested removal of metrics did not affect the overall index and the final index should therefore be more parsimonious.

## 3. Results and discussion

Index diagnostics suggested removing some originally selected (via model selection) metrics from the final model. The results presented here pertain to the final model, which includes five metrics (*TaxaBenthic*, *NumGuilds*, *TaxaNum*, *TaxaSelect*, and *Shannon*), unless otherwise noted (e.g., for metric selection, index diagnostics).

### 3.1. Metric selection

The DISTLM and BVSTEP models selected nine and three metrics, respectively. Two of the three metrics selected by the BVSTEP model were also selected by the DISTLM model; therefore, the original TBNI included 10 metrics (Table 2): *Shannon, Num_LR, NumES, NumGuilds, NumIndiv, NumSelect, NumTG, TaxaBenthic, TaxaNum, and TaxaSelect.* These metrics spanned diversity and richness, composition, occurrence, trophic structure, and focal species categories. Metrics from all but one of the categories initially considered were identified by the model-selection procedures. In other indices of biotic integrity, metric selection is either based on relationships with specific facets of ecological degradation (e.g., distance from point source pollution) or decisions by subject matter experts (e.g., Karr, 1981). The methodologies developed by Hallett et al. (2012a, 2012b) and that we adapted to the needs of the Tampa Bay ecosystem management community here were objective and statistically sound and did not rely on independent measures of ecological degradation.

### 3.2. Reference conditions

Reference conditions for each bay segment × season combination (Appendix D) were defined by the best portion of metric values observed during the study period. For several metrics selected by the models, reference conditions varied between bay segments in a given season and between seasons within bay segments. For example, *NumES* in Old Tampa Bay varied from 397 in the winter to 2,176 in the fall (Appendix D). This same metric was 231 in the winter in Middle Tampa Bay. Conversely, reference conditions for *TaxaSelect* were similar among all bay segments and seasons, ranging from three to four taxa. Ultimately, these conditions represent the best biological status since 1998 and although they do not characterize a pristine, nonimpacted state, they can be used as a viable reference point against which to examine ecosystem health (Hallett et al., 2012b).

Some authors have criticized using historical data to define the best available conditions because data collection methods are typically unstandardized and the data are of insufficient quantity or quality (Hughes, 1995; Harrison and Whitfield, 2004). We believe the historical data used in this study are robust responses to these critiques because they contain an 18-year dataset consistently collected via standardized protocols with a relatively high number of samples (N = 5,212). An additional concern is the need to account for natural spatiotemporal variability to minimize influences on index scores and therefore management responses. This was a valid concern for this index because the Tampa Bay nekton community exhibits pronounced spatiotemporal variability (Schrandt and MacDonald, 2020), and using bay segment and seasonal reference conditions addresses this concern.

### 3.3. Index scores

Resultant values in this section apply to the reduced-metric index, following the removal of some metrics after assessing index diagnostics (sections 2.7 and 3.5, respectively). For management and communication purposes, a "stoplight" color-coding system was established to describe a set of management benchmarks. After testing multiple percentiles and consulting with the TBEP on communication preferences, color/management response thresholds were set as follows, using the index scores from all samples (N = 5,212): ≥ 50th percentile (TBNI score ≥ 46) defined as green, < 50th percentile and ≥ 33rd percentile as yellow (TBNI scores between 32 and 46), and < 33rd percentile (TBNI score < 32) as red. These were deemed appropriate for communication purposes because they allow end users to visualize yearly variability without depicting unattainable goals (i.e., it is possible to attain green-level index scores but a score of 100 is probably not attainable). Additionally, the selected percentile cutoffs were deemed by managers to support an appropriate management response when the overall nekton community conditions reflected acute, rather than any chronic events that occurred over the period of record (e.g., see Section 2.6). As Perez-Dominguez et al. (2012) and others have asserted, "quality-class boundaries" can be highly subjective for nekton-based indices and therefore, the collaboration between fisheries scientists, bay resource managers, and our stakeholders under this project was essential to define and apply appropriate management thresholds to known perturbations to the nekton community of Tampa Bay.

Tampa Bay Nekton Index scores for individual net hauls ranged from 0 to 100 and averaged 46 over the entire development period (1998–2015), corresponding to a green, "Stay the Course" management response. Yearly index scores ranged from 37 (2005; yellow) to 52 (2015; green) (Fig. 2A). The comparatively low index score in 2005 coincides with the 2005 red tide event that affected fish communities in Tampa Bay and surrounding waters (e.g., Flaherty and Landsberg, 2011; Dupont et al., 2010). On the other hand, the TBNI increased in 2010 from previous years, which may seem counterintuitive because southwest Florida experienced colder than average winter temperatures in 2010. Indeed, these cold temperatures resulted in mortality of subadult/adult *Centropomus undecimalis* (Stevens et al., 2016), which is a dominant predator in the system. The increase in the TBNI could reflect the increased abundance of smaller individuals and juveniles of other taxa because of reduced predation pressure, or the short duration of the cold event may not be evident in the yearly index score. Schrandt and MacDonald (2020) also noted and discussed these trends when the Tampa Bay nekton were assessed with traditional univariate diversity indices and multivariate analyses. Overall, the TBNI generally increased from 2005 through 2015, perhaps indicating an improving, resilient nekton community. Yearly updates to the TBNI after the development period indicate some decline after 2015, but the TBNI has remained in the green, which we have defined here as representing a "healthy" nekton community.

Spatial variability in TBNI scores was evident (Fig. 2B), with scores varying among bay segments as well as by year. Generally, TBNI scores

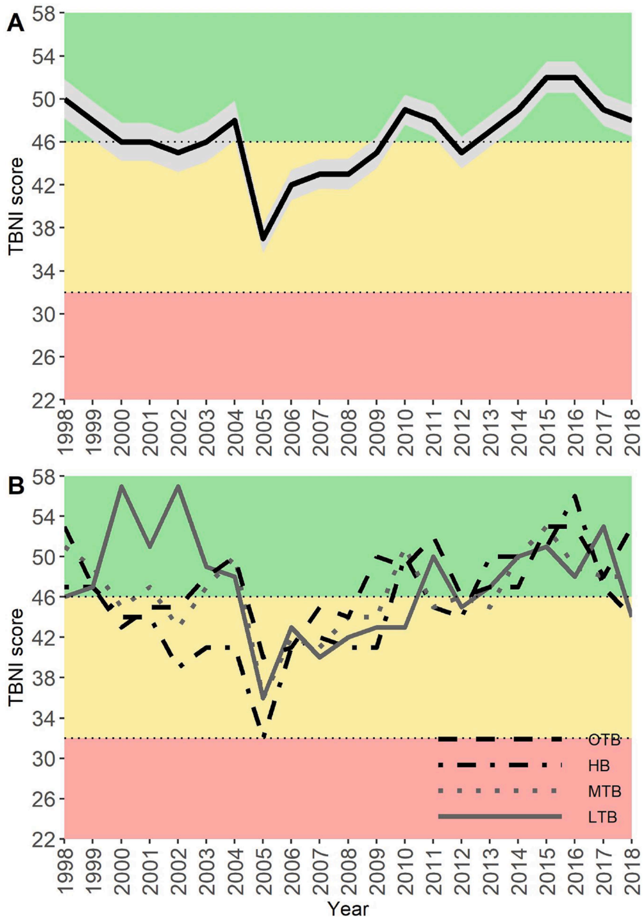


**Fig. 2.** Yearly Tampa Bay index scores, with standard error of the mean shown as shading around the line for the entire bay (A) and for each bay segment (B). OTB = Old Tampa Bay, HB = Hillsborough Bay, MTB = Middle Tampa Bay, LTB = Lower Tampa Bay. The final Tampa Bay Nekton Index integrates the number of taxa, the number of benthic taxa, the number of feeding guilds, the number of selected taxa, and the Shannon Weiner diversity index. Background colors in the graph are the "stoplight" color coding applied to the index to help guide management actions.

for Old Tampa Bay and Middle Tampa Bay were similar over time. Scores for Hillsborough Bay and Lower Tampa Bay were different from Old Tampa Bay and Middle Tampa Bay for multiple years. Hillsborough Bay had some of the lowest TBNI scores compared to the other bay segments through 2009, but then TBNI scores were more like those of Old Tampa Bay and Middle Tampa Bay after 2009.

### *3.4. Index sensitivity and reliability*

After calculating index scores, assessing sensitivity (response to degradation) and reliability (consistency) (Hallett et al., 2012b) was necessary to ensure the index responded appropriately to known environmental impacts. The TBNI score decreased in 2005 to the lowest annual score during the study period (Fig. 2), indicating an index sensitive to prolonged perturbations within Tampa Bay such as the 2005 red tide. Median yearly index scores before (48) and after (46) the event were greater than the score during the bloom year (36; Kruskal-Wallis test chi-squared = 43.151, df = 2, $P < 0.001$). Old Tampa Bay, Middle Tampa Bay, and Lower Tampa Bay collectively changed from green to yellow ("Caution Alert" management response) and Hillsborough Bay from yellow to red ("On alert" management response, Fig. 3). The TBNI scores increased the year after the event (Fig. 2), suggesting the TBNI has applicability for monitoring nekton community recovery among Tampa Bay segments following a major perturbation. Individual bay segments exhibited some variability in time to return to pre-bloom TBNI scores, with some segments requiring > 3 years. For example, Lower Tampa Bay nekton did not return to prebloom conditions for 6 years. Lower Tampa Bay, located at the mouth of the estuary, would have had the earliest and longest exposure to the 2005 red tide event, and the salinity (nearing oceanic salinities) in this segment is more conducive to the red tide organism's growth requirements (review by Vargo, 2009). The combination of these two factors most likely explains the prolonged recovery time of the index in this section of the bay.

Trends in the TBNI scores are similar to those found by Schrandt and MacDonald (2020), who assessed trends in the Tampa Bay nekton assemblage via more traditional methods such as biodiversity indices (i.e., species richness, Simpson's index) and multivariate analyses (i.e., permutational multivariate analysis of variance, similarity percentage analysis, non-metric multidimensional scaling ordination). The nekton assemblage in 2005 differed from that of other years and had increased abundances of small pelagic filter feeders (Schrandt and MacDonald, 2020), similar to findings in other red tide events in southwest Florida (Gannon et al., 2009). Additionally, a similar index response was detected for local red tide events by Hallett et al. (2012a, 2012b), who originally developed the methodologies applied here for use in a southwestern Australia estuary. This suggests the sensitivity of this index to ecological perturbations is robust and that these index methodologies are transferable to estuaries beyond the locale for which they are currently developed.

The yearly TBNI was temporally and spatially reliable, with monthly TBNI scores consistently varying among seasons and with greater variability than bay segment or season scores (Appendix E). Lowest index scores generally occurred in January each year. In 2010, the lowest score was in January but there was also a second low in December 2010, the lowest December score during the study period. The decline in the TBNI score in December in addition to January suggests the index can detect nekton response to monthly variation in environmental conditions (December 2010 was also colder than average but did not result in a *Centropomus undecimalis* mortality event), but when annually integrated, the index does not reflect potential short-term perturbations. Ultimately, this also suggests that the TBNI is robust with respect to seasonal variability within the estuary, thus providing additional assurance that it is a reliable tool for annually evaluating ecological health among Tampa Bay's management segments.

### *3.5. Index diagnostics*

Most of the 10 metrics selected for the TBNI showed the predicted relationship between the metric and index score (Table 3). The metrics *TaxaBenthic*, *NumGuilds*, *TaxaNum*, *TaxaSelect,* and *Shannon* had positive correlations with the TBNI score ($r > 0.75$). Metrics with lower positive correlations ($r < 0.2$) included *NumES*, *NumIndiv*, *Num_LR*, *NumSelect*, and *NumTG*. The two metrics predicted to have negative correlations with the index (*NumIndiv* and *NumTG*) had weak positive relationships ($r = 0.104$ and 0.105, respectively). These correlation coefficients were used to help reduce metrics included in the final index; it has been suggested that metrics that do not display the predicted relationship with the index score should be removed from the final index (Hughes et al., 1998). Therefore, it was plausible to remove *NumIndiv* and *NumTG* because these metrics had relationships that were contrary to predictions.

Principal Components (PC) Analysis of TBNI scores produced the expected result for an index that incorporates consistent metrics. The first PC was characterized by all 10 metrics, in a positive direction (Table 3). The four predominant metrics for PC1 were *TaxaNum*, *TaxaBenthic*, *NumGuilds,* and *TaxaSelect*. The metric with the lowest contribution to PC1 was *Num_LR*. The first PC and the TBNI score were positively correlated ($r = 0.997$), suggesting that *TaxaNum*, *TaxaBenthic*, *NumGuilds,* and *TaxaSelect* are important metrics in the TBNI.

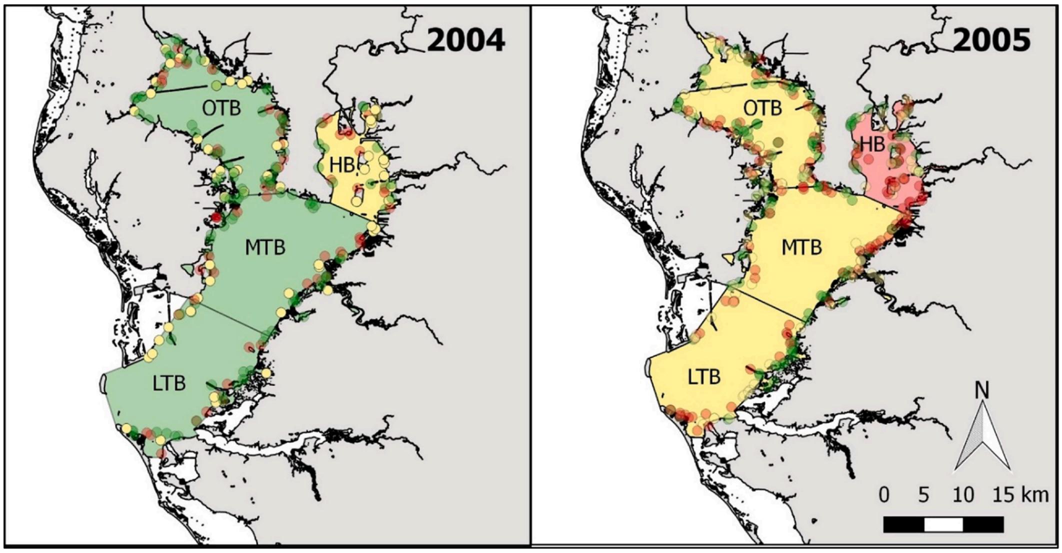


**Fig. 3.** An example of map color coding of the Tampa Bay Nekton Index to communicate yearly bay status. In 2005, a severe red tide event affected the Tampa Bay area, and the Tampa Bay Nekton Index scores declined from 2004 (prebloom) to 2005 (during the bloom). Circles represent sampling locations. OTB = Old Tampa Bay, HB = Hillsborough Bay, MTB = Middle Tampa Bay, LTB = Lower Tampa Bay. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 3**
Tampa Bay Nekton Index diagnostic results. Pearson correlation coefficient (r) between the originally selected metrics and the Tampa Bay Nekton Index score; metrics with correlation coefficients < 0.7 were ultimately removed from the final index. Eigenvectors for metric scores from Principal Component 1 (PC1).

| Metric | Correlation (r) with TBNI | PC1 Eigenvector |
|---|---|---|
| *TaxaNum* | 0.895 | 0.436 |
| *TaxaBenthic* | 0.895 | 0.431 |
| *NumGuilds* | 0.824 | 0.423 |
| *TaxaSelect* | 0.792 | 0.436 |
| *Shannon* | 0.752 | 0.330 |
| *NumSelect* | 0.074 | 0.238 |
| *NumIndiv* | 0.104 | 0.139 |
| *NumTG* | 0.105 | 0.139 |
| *NumES* | 0.084 | 0.177 |
| *Num_LR* | 0.070 | 0.135 |

To avoid overparameterization of the final index, we chose to remove metrics that had relatively low correlation coefficients (< 0.7) compared to other metrics when correlated with the index score (*NumES*, *NumIndiv*, *Num_LR*, *NumSelect*, and *NumTG*). Presumably, these metrics would have low concordance with the TBNI. Additionally, two of these metrics (*NumIndiv* and *NumTG*) had relationships to the TBNI score that were contrary to *a priori* predictions and were identified by another means (see above) for removal (Hughes et al., 1998). The index was re-calculated after removal of the unnecessary metrics, and the correlation coefficient between the original and reduced-metric indices was 0.97, indicating that near-similar results would be obtained from either index. Therefore, we ultimately applied the reduced-metric index for Tampa Bay because it was more parsimonious. The final TBNI includes five metrics: *TaxaBenthic*, *NumGuilds*, *TaxaNum*, *TaxaSelect*, and *Shannon*.

### *3.6. The TBNI as a local communication and management tool*

As a management tool, the TBNI can be interpreted as a generalized view of overall aquatic health since nekton communities respond to a variety of in-situ and watershed conditions. For instance, if a bay segment is in the yellow "Caution Alert" zone for multiple years, then an appropriate management action would be to direct focused research or enhanced monitoring toward understanding the perceived declines in nekton community structure. Likewise, if the index remained in the red "On Alert" zone for multiple years (e.g., > 2 years), then immediate management action would be warranted to address perceived perturbation(s) to the nekton community structure to promote its recovery to more stable conditions. This makes the TBNI invaluable in continually and comprehensively monitoring estuarine ecosystem conditions. However, it should be noted that the TBNI is not intended to identify specific activities or disturbances that cause estuary degradation (e.g., nutrient loading, habitat loss or fragmentation, freshwater input changes), because the index integrates nekton community metrics that potentially respond to multiple stressors. Regardless, it is evident that single, extreme events or disturbances can acutely affect index scores, and appropriate management responses would be justified over protracted periods of non-recovery.

The quantile-based color scheme for communicating the TBNI is useful as a reporting tool to resource managers and policymakers alike (Hallett, 2014). Annual TBNI status updates will be relatively simple to calculate and report utilizing open-science tools (e.g., https://tbeptech.github.io/tbeptools), and it is envisioned that the TBNI would complement other ecosystem health indices used by the TBEP (e.g., https://shiny.tbep.org/wq-dash/). Furthermore, the TBNI can easily be communicated via different presentation techniques like color-coding figures and/or maps (Longstaff et al. 2010). These products are accessible through an online, interactive dashboard where stakeholders can view results and download relevant data and summary graphics for the TBNI (https://shiny.tbep.org/nekton-dash). The TBNI can be calculated using functions provided in the tbeptools R package (https://tbep-tech.github.io/tbeptools; Beck et al., 2020; R Core Team, 2020). These functions include methods for importing raw data through direct download from FWRI web links, summarizing these data to calculate metric and overall TBNI scores, and plotting summary graphics for report cards and time series results. A detailed vignette describing how to install the package and use the functions is available on the tbeptools web page (https://tbep-tech.github.io/tbeptools/articles/tbni.html). The Shiny web-based dashboard (Chang et al., 2020) is available to view results, download graphics, and download raw data for the TBNI (https://shiny.tbep.org/nekton-dash/, Beck 2020). The dashboard includes summarized information for Tampa Bay and spatially-referenced information for specific sampling sites.

As a result of the development of an index and supporting communication tools, stakeholders can 1) use the index to monitor and track ecosystem health over time (e.g., in response to a disturbance); 2) influence general management decisions and leverage monetary support for restoration activities or monitoring; 3) identify priority areas for conservation/preservation (Schoolmaster et al. 2012) and/or areas in need of additional investigation to identify the source of degradation; and 4) be generally informed about the status and condition of natural systems. Lastly, although the TBNI is specific to Tampa Bay and its best-available reference conditions, an expanded index could be developed and applied at larger region or statewide scales, if the data are available (like they are for multiple estuaries in Florida). This could aid in monitoring, managing, and comparing the important nekton resources supporting broad coastal communities. In applying the index in this manner, managers would be able to assess and compare ecological status of one estuary to another (given each estuary's individual reference conditions) and could help guide the sustainable use of economically and culturally significant but limited resources.

## 4. Conclusions

The nekton index developed here used objective approaches like the indices developed for southwestern Australia (Hallett et al., 2012a, 2012b) to provide an index to communicate general nekton status of the Tampa Bay estuary. It is also based on abundant data of mostly young-of-the-year individuals, so it is likely to quickly detect deleterious nekton community changes following ecological degradation. Generally, the long-term trend of the TBNI depicts stability and resistance of the nekton functional structure within the Tampa Bay estuarine system over contemporary periods, when other improving ecosystem indicators have been observed (Greening et al., 2014; Karlen et al., 2015; Sherwood et al., 2017). Additionally, the nekton community, as represented by the annual TBNI, seems to return quickly to midrange levels ("Stay the Course" management response) when there are peaks or valleys in index scores, suggesting resilience of nekton communities in Tampa Bay. Similar conclusions were reached by Schrandt and MacDonald (2020), suggesting that the TBNI and the management thresholds defined herein confidently reflect nekton community changes over time in a manner that would prompt an appropriate management response to a prolonged perturbation event. We have also provided open-science tools to make the methodology, calculations, and results accessible in an online format to extend the reach of communicating the results annually to multiple stakeholder groups. Lastly, the methodology used to develop this index could be applied to other systems, including potentially developing a regional index wherein reference conditions are system-specific so that comparisons could be made among estuaries and could help guide the use of limited resources.

## CRediT authorship contribution statement

**Meagan N. Schrandt:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Timothy C. MacDonald:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Edward T. Sherwood:** Conceptualization, Supervision, Project administration, Funding acquisition, Resources, Writing - review & editing, Visualization. **Marcus W. Beck:** Conceptualization, Methodology, Software, Writing - review & editing, Visualization.

## 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.

## Acknowledgements

We thank the staff of the Florida Fish and Wildlife Research Institute's Fisheries-Independent Monitoring program in Tampa Bay for their dedication to annual monitoring to produce the long-term dataset. The progress achieved in restoring the Tampa Bay ecosystem over recent decades would not be possible without the steadfast commitments to routinely monitor and assess the Bay's condition. The Tampa Bay Estuary Program helped fund the analyses that developed the index and its staff was instrumental in decisions regarding communication of the index. TBEP funding for this project stems from EPA Section 320 Grant Funds, and the TBEP's local government partners (Hillsborough, Manatee, Pasco, and Pinellas Counties; the Cities of Clearwater, St. Petersburg, and Tampa; Tampa Bay Water; and the Southwest Florida Water Management District) through contributions to the TBEP's operating budget. We also thank R. Muller, and R. Paperno, whose comments improved this manuscript.

## Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107310.

## References

Beck, M.W. 2020. tbep-tech/nekton-dash: v1.0 (Version v1.0). Zenodo. http://doi.org/10.5281/zenodo.3939236.
Beck, M.W., Schrandt, M.N., Wessel, M., Sherwood, E.T., Best, B.D. 2020. tbeptools: Data and Indicators for the Tampa Bay Estuary Program. R package version 0.0.1. https://github.com/tbep-tech/tbeptool.
Bilkovic, D.M., Hershner, C.H., Berman, M.R., Havens, K.J., Stanhope, D.M., 2005. Evaluating nearshore communities as indicators of ecosystem health. In: Bortone, S. A. (Ed.), Estuarine Indicators. CRC Press, Boca Raton, Florida, pp. 365–379.
Borja, A., Bricker, S.B., Dauer, D.M., Demetriades, N.T., Ferreira, J.G., Forbes, A.T., Hutchings, P., Jia, X., Kenchington, R., Marques, J.C., Zhu, C., 2008. Overview of integrative tools and methods in assessing ecological integrity in estuarine and coastal systems worldwide. Mar. Pollut. Bull. 56, 1519–1537.
Chang, W., Cheng, J., Allaire, J.J., Xie, Y., McPherson, J. 2020. shiny: Web Application Framework for R. R package version 1.5.0. https://CRAN.R-project.org/package=shiny.
Clarke, K.R., Ainsworth, M., 1993. A method of linking multivariate community structure to environmental variables. Mar. Ecol. Prog. Ser. 92, 205–219.
Clarke, K.R., Gorley, R.N., Somerfield, P.J., Warwick, R.M., 2014. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation, third ed. PRIMER-E, Plymouth, United Kingdom.
Deegan, L.A., Finn, J.T., Ayvazian, S.G., Ryder-Kieffer, C.A., Buonaccorsi, J., 1997. Development and validation of an estuarine biotic integrity index. Estuaries 20, 601–617.
Dupont, J.M., Hallock, P., Jaap, W.C., 2010. Ecological impacts of the 2005 red tide on artificial reef epibenthic macroinvertebrate and fish communities in the eastern Gulf of Mexico. Mar. Ecol. Prog. Ser. 415, 189–200.
DWAF, 1998. South African National Water Act; Act 36 of 1998, Department of Water Affairs and Forestry, South Africa. www page, http://www.dwaf.gov.za/iwqs/nwa/index.html [Last accessed August 2019].
Elliott, M., Whitfield, A.K., Potter, I.K., Blader, S.J.M., Cyrus, D.P., Nordlie, F.G., Harrison., T.D., 2007. The guild approach to categorizing estuarine fish assemblages: a global review. Fish. Fish. 8, 241–268. https://doi.org/10.1111/j.1467-2679.2007.00253.x.
Community, European, 2000. Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. Off. J. Eur. Commun. L327, 1–72.
Ferreira, J.G., Vale, C., Soares, C.V., Salas, F., Stacey, P.E., Bricker, S.B., Silva, M.C., Marques, J.C., 2007. Monitoring of coastal and transitional waters under the E.U. Water Framework Directive. Environ. Monit. Assess. 135, 195–216.
Flaherty, K.E., Landsberg, J.H., 2011. Effects of a persistent red tide (*Karenia brevis*) bloom on community structure and species-specific relative abundance of nekton in a Gulf of Mexico estuary. Estuar. Coast. 34, 417–439. https://doi.org/10.1007/s12237-010-9350-x.
Gannon, D.P., Berens McCabe, E.J., Camilleri, S.A., Gannon, J.G., Brueggen, M.K., Barleycorn, A.A., Palubok, V.I., Kirkpatrick, G.J., Wells, R.S., 2009. Effects of *Karenia brevis* harmful algal blooms on nearshore fish communities in southwest Florida. Mar. Ecol. Prog. Ser. 378, 171–186.
Gibson, G.R., Bowman, M.L., Gerritsen, J., Snyder, B.D., 2000. Estuarine and coastal marine waters: bioassessment and biocriteria technical guidance. USEPA report 822-B-00-024. Office of Water, Washington DC, p. 300.
Greening, H.S., Cross, L.C., Sherwood, E.T., 2014. Ecosystem responses to long-term nutrient management in an urban estuary: Tampa Bay, Florida, USA. Estuar. Coast. Shelf S. 151, A1–A16.

Hallett, C.S., 2010. The development and validation of an estuarine health index using fish community characteristics. PhD thesis, Murdoch University, Perth, WA, 209 pp. Available from http://researchrepository.murdoch.edu.au/.

Hallett, C.S., 2014. Quantile-based grading improves the effectiveness of a multimetric index as a tool for communicating estuarine condition. Ecol. Indic. 39, 4–87.

Hallett, C.S., Valesini, F.J., Clarke, K.R., 2012a. A method for selecting health index metrics in the absence of independent measures of ecological condition. Ecol. Indic. 19, 240–252. https://doi.org/10.1016/j.ecolind.2011.07.002.

Hallett, C.S., Valesini, F.J., Clarke, K.R., Hesp, A.A., Hoeksema, S.D., 2012b. Development and validation of fish-based multimetric indices for assessing the ecological health of Western Australia estuaries. Estuar. Coast. Shelf S. 104, 102–113. https://doi.org10.1016/j.ecss.2012.03.006.

Harrison, T.D., Whitfield, A.K., 2004. A multimetric fish index to assess the environmental condition of estuaries. J. Fish. Biol. 65, 683–710. https://doi.org/10.1111/j.0022-1112.2004.00477.x.

Harrison, T.D., Whitfield, A.K., 2006. Application of a multimetric fish index to assess the environmental condition of South African estuaries. Estuar. Coast. 29, 1108–1120.

Hughes, R.M., 1995. Defining acceptable biological status by comparing with reference conditions. In: Davis, W.S., Simon, T.P. (Eds.), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, Boca Raton, Florida, pp. 31–47.

Hughes, R.M., Kaufmann, P.R., Herlihy, A.T., Kincaid, T.M., Reynolds, L., Larsen, D.P., 1998. A process for developing and evaluating indices of fish assemblage integrity. Can. J. Fish. Aquat. Sci. 55, 1618–1631.

Janicki, A.J., Wade, D., Pribble, J.R., 2000. Development of a process to track the status of chlorophyll and light attenuation to support seagrass restoration goals in Tampa Bay. Tampa Bay Estuary Program Technical Publication #04-00. St. Petersburg, Florida.

Karlen, D.J., Dix, T.L., Goetting, B.K., Markham, S.E., Campbell, K.W., Jernigan, J.M., 2015. Twenty-year trends in the benthic community and sediment quality of Tampa Bay 1993-2012. Tampa Bay Estuary Program Technical Publication #04-15. St. Petersburg, Florida.

Karr, J.R., 1981. Assessment of Biotic Integrity Using Fish Communities. Fisheries. 6, 21–27. https://doi.org/10.1577/1548-8446(1981)006<0021:AOBIUF>2.0.CO;2.

Karr, J.R., 1991. Biological integrity: a long-neglected aspect of water resource management. Ecol. Appl. 1, 66–84.

Longstaff, B.J., Carruthers, T.J.B., Dennison, W.C., Lookingbill, T.R., Hawkey, J.M., Thomas, J.E., Wicks, E.C., Woerner, J., 2010. Integrating and applying science: A practical handbook for effective coastal ecosystem assessment. IAN Press, Cambridge, Maryland, p. 244.

Malloy, K.J., Wade, D., Janicki, A., Grabe, S.A., Nijbroek, R., 2007. Development of a benthic index to assess sediment quality in the Tampa Bay Estuary. Mar. Pollut. Bull. 54, 22–31.

McArdle, B.H., Anderson, M.J., 2001. Fitting multivariate models to community data: a comment on distance-based redundancy analysis. Ecology 82, 290–297. https://doi.org/10.1890/0012-9658(2001)082[0290:FMMTCD]2.0.CO;2.

Perez-Dominguez, R., Maci, S., Courrat, A., Lepage, M., Borja, A., Uriarte, A., Neto, J.M., Cabral, H., St. Raykov, V., Franco, A., Alvarez, M.C., Elliott, M., 2012. Current developments on fish-based indices to assess ecological-quality status of estuaries and lagoons. Ecol. Indicat. 23, 34-35. Doi: 10.1016/j.ecolind.2012.03.006 .

Potter, I.C., Tweedley, J.R., Elliott, M., Whitfield, A.K., 2015. The ways in which fish use estuaries: a refinement and expansion of the guild approach. Fish. Fish. 16, 230–239. https://doi.org/10.1111/faf.12050.

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/.

Schoolmaster, D.R., Grace, J.B., Schweiger, E.W., 2012. A general theory of multimetric indices and their properties. Methods. Ecol. Evol. 3, 773–781.

Schrandt, M.N., MacDonald, T.C., 2020. Long-term stability of the faunal community of a subtropical estuary: evaluating disturbances in the context of interannual variability. Estuar. Coast. 43, 347–359.

Sherwood, E.T., Greening, H.S., Johansson, J.O.R., Kaufman, K., Raulerson, G.E., 2017. Tampa Bay (Florida, USA): Documenting seagrass recovery since the 1980's and reviewing the benefits. Southeastern Geograp. 57, 294–319.

Stevens, P.W., Blewett, D.A., Boucek, R.E., Rehage, J.S., Winner, B.L., Young, J.M., Whittington, J.A., Paperno, R., 2016. Resilience of a tropical sport fish population to a severe cold event varies across five estuaries in southern Florida. Ecosphere 7 (8), e01400. https://doi.org/10.1002/ecs2.1400.

Southwest Florida Water Management District, 2011. Land Use/Cover GIS Shapefiles. Accessed July 2019. https://data-swfwmd.opendata.arcgis.com/datasets/2011-land-use-land-cover.

Tampa Bay Estuary Program (TBEP). 2017. Charting the Course 2017: the Comprehensive Conservation and Management Plan for Tampa Bay. Tampa Bay Estuary Program, St. Petersburg, Florida, pp. 158.

Tampa Bay Regional Planning Council Economic Analysis Program, 2014. Economic Evaluation of Tampa Bay. St. Petersburg, Florida, pp. 140.

Uriarte, A., Borja, A., 2009. Assessing fish quality status in transitional waters, within the European Water Framework Directive: Setting boundary classes and responding to anthropogenic pressures. Estuar. Coast. Shelf Sci. 82, 214–224.

Vargo, G.A., 2009. A brief summary of the physiology and ecology of *Karenia brevis* (G. Hansen and Moestrup comb. Nov.) red tides on the West Florida Shelf and of hypotheses posed for their initiation, growth, maintenance, and termination. Harmful Algae. 8, 573–584.

Woodward, G., Gessner, M.O., Giller, P.S., Gulis, V., Hladyz, S., Lecerf, A., Malmqvist, B., McKie, B.G., Tiegs, S.D., Cariss, H., Dobson, M., Elosegi, A., Ferreira, V., Graca, M.A.S., Fleituch, T., Lacoursiere, J.O., Nistorescu, M., Pozo, J., Risnoveanu, G., Schindler, M., Vadineanu, A., Vought, L.B.M., Chauvet, E., 2012. Continental-scale effects of nutrient pollution on stream ecosystem functioning. Science. 336, 1438–1440. https://doi.org/10.1126/science.1219534.