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A quantitative and qualitative decision-making process for selecting indicators to track ecosystem condition

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ABSTRACT

Ecosystem indicators are a well-established method for tracking ecosystem conditions and trends with the purpose of informing ecosystem-based management. The selection of indicators is a key step in the management process; however, because 1) selection can be inherently subjective 2) researchers can be entrenched in the ecosystem components they routinely measure, and 3) some voices may be marginalized in a group setting, the selection, prioritization, and consensus processes can be challenging. To overcome these issues, an indicator selection process was developed herein that incorporated expert opinion both qualitatively and quantitatively. The decision matrix asked experts to provide weighted values for each selection criterion and a score of how well each potential indicator fit each criterion. The score of how well the indicators fit the criterion was multiplied by the weight given to that criterion, then summed for all criteria, resulting in an overall score of how well a potential indicator fit the criteria. The indicator scores were then ranked using all experts' scores to develop a single best-fit list of indicators. The approach was pilot-tested to select indicators for the Florida Keys National Marine Sanctuary (FKNMS), creating a prioritized list of indicators that best reflected the condition of the FKNMS resources, ecosystem services, and pressures. Specifically, 56 indicators were found to best model the status and trends associated with 16 standard questions regarding condition of national marine sanctuaries. This process is directly transferable to other national marine sanctuaries, and also identifies data gaps. The criteria can be modified to make the selection process applicable to a wide range of ecosystem-based management applications in both marine and terrestrial ecosystems. This method provides a means of selecting indicators that minimizes the effects of group dynamics on consensus.

1. Introduction

Integrated Ecosystem Assessments (IEAs) are a scientific approach to inform ecosystem-based management (EBM). As such, IEAs are a framework for organizing science in a manner that informs EBM decisions at multiple scales and across sectors [12]. The IEA approach incorporates an understanding of the whole social and ecological system, not simply the individual components, into the decision making process management of marine ecosystems, allowing managers to balance trade-offs and determine what management action or scenario is more likely to achieve their desired goal(s) (Harvey et al., 2018). IEAs and EBM, in general, use indicator-based assessments of ecosystem status [12]. The use of ecosystem indicators is a widely used method to monitor condition and trends. Indicators are quantitative measurements that serve as proxies for characterizing natural and socioeconomic systems [11]. When assembled effectively, the full suite of indicators detects changes in ecosystem conditions and processes, giving managers the ecosystem-based information necessary to evaluate current and past decisions, as well as inform future ones [9]. Thus, the selection of the optimal suite of indicators is a key step towards implementing successful EBM.

However, selection and consensus processes can be a challenge due to inertia in expert opinion, high participant time commitment, travel cost, earnings lost, and the resulting polarization in decision making [14]. Traditional decision making processes, such as public hearings, will be dominated by extreme viewpoints if participation costs are high

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[22]. In addition, the input of underrepresented groups, such as women and people of color, is likely to be marginalized in groups ([6]), though equal input in decision making is crucial for successful deliberation [18]. Therefore, an indicator selection method with low time commitment requirement that minimizes the effects of group dynamics is essential in order to yield a more objective result.

The first step to assessing an ecosystem's condition and health is identifying, selecting, and developing indicators that capture the status and trends of key ecosystem components. These indicators should be representative of the status and trends of individual components (including biophysical, human activity, community vulnerability, and human indicators), but also collectively reflect the condition and trajectory of the entire socio-ecological system. In past efforts ([5,13,20]), good indicators have been defined to be scientifically rigorous, understandable to/resonate with stakeholders, sensitive to changes in the system, and trusted in the decision-making process. Moreover, the indicators must also have rigorous, consistent long-term monitoring data available, in order to be assessed.

The NOAA Office of National Marine Sanctuaries (USA) regularly produces "Condition Reports" that provide a summary of the current condition and trends of resources in the sanctuary, ecosystem services, pressures on those resources, and management responses to the pressures that threaten the integrity of the marine environment. Condition reports include information on the status and trends of water quality, habitat quality, living marine resources, ecosystem services, maritime heritage resources, and the human activities that affect them [21]. Condition reports depend on the selection of robust, vetted, useful indicators to underlie conclusions they make about the status and trends of sanctuary resources, ecosystem services, and pressures.

In 2009, the NOAA Office of National Marine Sanctuaries (ONMS) received a letter from stakeholders requesting a more transparent, quantitative, expert-reviewed process for selection of indicators used in sanctuary condition reports [2]. In the past, first iterations of condition reports relied heavily upon expert opinion to determine ratings and responses for each resource question. Although indicators and data sets were often selected in consultation with outside experts, the approach was criticized for a lack of transparency and repeatability over time. To improve the process, it was suggested that the approach should include quantitative measures of ecosystem indicators derived from regional monitoring data, supplemented by qualitative interpretations derived from expert opinions and local knowledge. This would allow for a more transparent and repeatable process in the future.

The Florida Keys National Marine Sanctuary (FKNMS) is located beyond the southern tip of the Florida Peninsula. It includes the waters surrounding the Florida Keys archipelago archiin both the Atlantic Ocean and Gulf of Mexico. FKNMS has a trove of natural resources, including more than 6000 species of marine life, coral reef and hard-bottom habitats, valuable fisheries communities, seagrass beds, and mangrove fringed islands ([8] and [23]). It is historically characterized by oligotrophic, relatively good water quality [1]. The FKNMS supports more than 33,000 jobs, supports 58% of the local economy and accounts for over $2.3B in annual sales (FKNMS fact sheet). In 1990, the Florida Keys was designated as a national marine sanctuary to protect its resources and provide for the education and interpretation of these resources for the good of the public.

FKNMS last produced a condition report in 2011. However, since then, the ecosystem condition and human activities affecting the FKNMS have changed dramatically due to climate change, increased human population, extractive resource use, recreational use, coral disease outbreaks, nutrient loading, and other pressures [15]. Therefore, there is a need for current best information for an updated sanctuary condition report that relies on indicators that capture and reflect changes since 2011. These indicators will provide managers and stakeholders with status and trends of conditions as well as early warnings of potential resource degradation that will allow for more informed and effective management decisions. To comply with the 2009 request from stakeholders, this update should have quantitative indicators underlying the report and a clear and transparent selection process for the indicators. Though many resource management processes, such as indicator selection, rely upon expert consensus, there are few industry standards in reaching an agreement while including a group's full input ([13]). Thus, the indicator selection process has been approached with a variety of methods across different ecosystems (e.g., [5,12], and [13]). A framework that integrates quantitative and qualitative input to identify and prioritize potential indicators to assess ecosystem status would be a significant improvement to indicator selection methodologies.

Herein, we developed and piloted a clear, transparent process that integrates qualitative and quantitative information from experts in a decision criteria matrix to identify, evaluate, and prioritize most useful and relevant indicators for the FKNMS. The indicator selection process described will aid in the revision and update on the status and trends of sanctuary condition, as well as provide indicators for use in future management effectiveness evaluation and interventions. The described process also provides a way to capture and equally represent often diminished voices of underrepresented groups in indicator selection [6], while also reducing the participation cost of a lengthy decision making process, which will therefore reduce polarization of viewpoints [22]. This selection method could be applied to any decision-making process requiring consensus from expert knowledge to streamline and standardize input both individually and from a group of experts.

2. Materials and methods

The indicator selection process consisted of five steps (Fig. 1), all of which were conducted with significant collaboration and input from our management partners at FKNMS. The process was designed to harness expert opinion to both identify potential indicators and select the top indicators that best met agreed upon criteria in an impartial manner, while minimizing group dynamics that obstruct objectivity and equal input. Thus, the indicator selection process centered around gathering expert opinion via a workshop and quantitative individual scoring of potential indicators against consensus criteria in a matrix, using assigned scores and weights of importance of criteria (Table 1). This combined qualitative and quantitative method solves problems with indicator selection in that it allows individual voices, from sometimes marginalized populations, to be equally heard in a group setting.

2.1. Step 1. Draft indicator criteria and identification of experts

The indicator selection process (Fig. 1) began with a literature review of previous work that used indicators in the region as well as established indicator criteria from environmental studies across the globe [5,7,13,17,28]. These local and global sources of indicator criteria, in conjunction with the characteristics required for informing a sanctuary condition report, resulted in a preliminary list of criteria that a potential indicator should meet to be usable and appropriate for the project's format and the sanctuary's needs.

The draft set of criteria was established to determine if a proposed ecosystem indicator 1) was an appropriate representation of ecosystem condition and 2) aligned with the National Marine Sanctuary Condition Report format. The draft criteria were: **long-term data availability, importance to the ecosystem and culture, responsiveness to changes in environmental conditions, measurability, relevance to sanctuary condition report questions, and responsiveness to management actions.** These criteria were then presented at the expert workshop to determine whether they were the most appropriate for the intended purpose or if they needed to be modified. In addition to the criteria, an initial draft list of proposed indicators was developed for each of the six sections of a condition report. These lists were first attempts, intended to initiate conversation by expert participants on potential indicators to add and remove.

The goal when selecting the workshop participants was to identify a

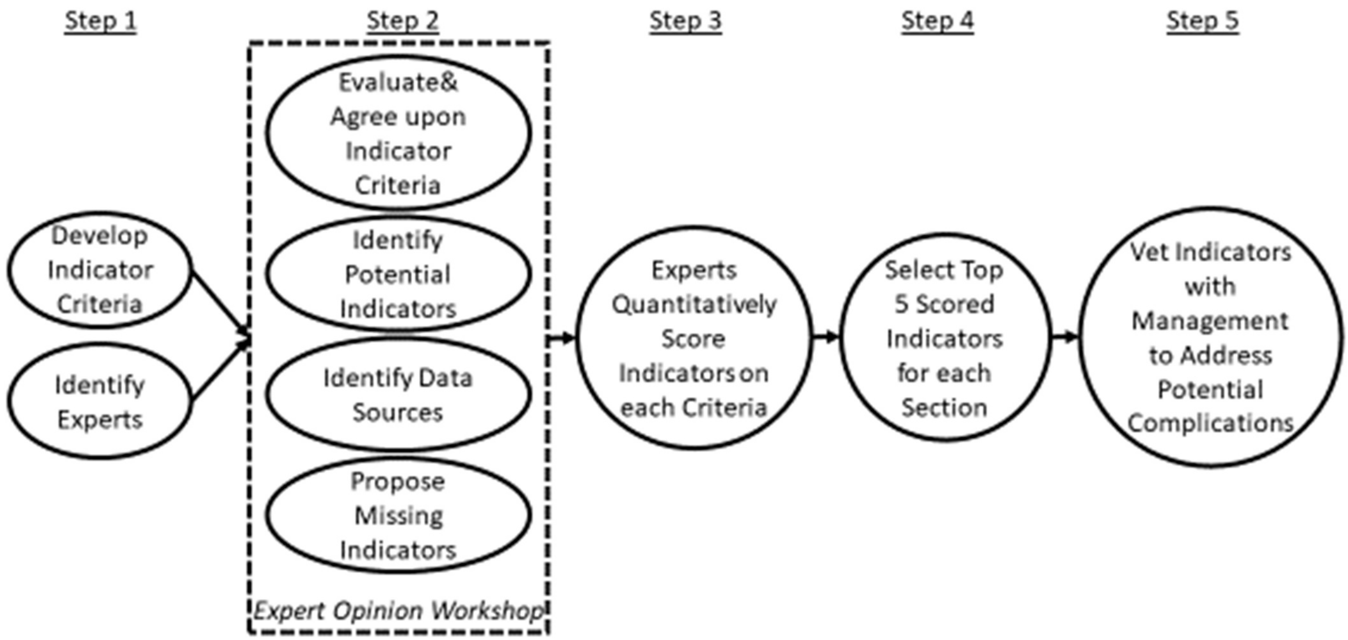

Fig. 1. The 5-step indicator selection process centered around an expert opinion workshop and frequent collaboration with the resource managers that intended to use the indicators.

Table 1
Example expert-completed decision matrix from Step 3. This example includes decided upon criteria (column titles) and cells for every indicator proposed by the group or team (row titles). The total score is calculated by multiplying the expert-selected score in cell by the set weight of importance of each criterion, then summing these products for each proposed indicator per criterion. The total score represents the appropriateness of each proposed indicator considering the criteria.

FKNMS Ecosystem Indicators Selection Decision Matrix							
	Decision Criteria						
	Long term data availability	Importance to ecosystem and culture (keystone, architect, poster-child)	Responsiveness to environmental changes	Measurability	Relevance to Sanctuary condition report question 9-eutrophic condition	Responsiveness to management actions	
Criteria weights	**5**	**4**	**3**	**2**	**5**	**4**	**Total score**
Proposed indicators							
Total carbon	6	6	6	6	9	6	216
Light profiles	3	6	3	3	6	3	159
CDOM	9	9	9	9	9	6	270
Salinity	3	6	6	6	6	6	186
Phytoplankton	6	9	9	6	6	9	288
SRP	9	9	9	9	9	9	273

group of experts relevant to FKNMS. Working with FKNMS managers, the expert invitee list drew from a wide range of backgrounds, areas of expertise, affiliations, interactions with FKNMS, and monitoring efforts. A poll of availability was conducted prior to scheduling the workshop to ensure as many experts as possible from many fields of expertise and affiliations were able to attend.

2.2. Step 2. Expert opinion workshop

The overarching goal of the expert workshop was to garner expert opinion, advice, and feedback for the selection of proposed ecological and socioeconomic indicators for FKNMS resources. The objectives of the workshop were to 1) reach a consensus on what makes a good indicator for the sanctuary's process, including the relevant criteria, 2) develop a comprehensive list of proposed indicators for each condition report section, 3) identify existing data sources and gaps, and 4) propose "missing indicators" for which sufficient data do not currently exist, but should be considered in the future.

The workshop began with an introduction of the Integrated Ecosystem Assessment approach and the needs of the FKNMS, including a discussion of the draft indicator criteria. Then, a presentation was given to communicate the purpose, requirement, format and history of condition reports for National Marine Sanctuaries. ONMS condition reports aim to provide a summary of resources in each sanctuary, pressures on those resources, and the current condition and trends. Specifically, the reports include information on the status and trends of six sections: sanctuary water quality, habitat, living resources, maritime heritage resources, ecosystem services, and the human activities that affect them [25]. The experts were then given time to refine the indicator criteria and discuss the final criteria that should be used henceforth to evaluate the proposed indicators.

Experts were each assigned to a breakout group based upon their expertise relative to the six sections of the ONMS condition reports. In the breakout groups, experts discussed the prepared draft list of possible indicators relevant to their condition report questions. These initially proposed indicators provided a starting point for each group to add and remove proposed indicators. The groups were then asked to consider potential indicators without current data sources so as to include potential missing indicators that might be an improvement upon currently monitored indicators, to show data gaps. The result was a proposed indicator list that included those from monitoring data as well as these missing indicators not currently being monitored sufficiently.

All breakout groups came together, and a member from each group presented their proposed indicators to the entire group, allowing for discussion and inclusion of proposed indicators, data sources and gaps, and missing indicators with all experts at the workshop. The final product was a comprehensive list of proposed indicators (Table 2) along with background rationale for each.

2.3. Step 3. Quantitatively score indicators

Using the indicator criteria agreed upon at the expert workshop, a decision criteria matrix was created (Table 1). The matrix allowed experts to individually score each proposed indicator's fit for each decision criterion (Table 1). Experts could also individually select the weights assigned to each criteria, setting for importance (Table 1). The decision matrix enabled the collection of individual quantitative data to measure how well each proposed indicator meets each of the criterion according to each expert. This allows all participant experts to have equal input into the prioritization process rather than conducting the scoring in a workshop setting where group dynamics can have a disproportionate effect on the scoring. These individual scores can then be analyzed together to determine the group score for the proposed indicators' fit to the criteria along with relative weights for each criterion. The process thus allows for both group rationale and individual input, without succumbing to the lengthy review process and indicator decision making inertia that have arisen in similar group consensus processes, as well as the "championing" of specific existing monitoring programs or "pet" projects [10,14].

At the conclusion of the workshop, experts were instructed on how to use the decision matrix to score the proposed indicators against the criteria. They were tasked with completing their decision matrices individually and electronically submitting them to the process team. To weight the criteria, each individual assigned a "weight of importance" from 0 to 5 to each criterion from a drop down menu, with a value of 5 representing the most important decision criterion and 0 representing no importance. The matrix allowed for values of criteria weights to be repeated; thus, it was not scored in rank order of importance, but by relative weight of importance. This also could allow for equal weighting of all criteria. To score how well each indicator met each criteria, experts selected a score of 0, 3, 6 or 9 from a drop down menu in each cell of the matrix, ranging from the criterion not being met at all (0) to the criterion being met as best as possible (9). The cell is the intersection of each proposed indicator with each decision criterion. The score represents how well the indicator met that criterion compared to other proposed indicators (Table 1). Scoring with separated integers rather than consecutive integers was designed to allow for score clustering and well-defined "winners" [24].

Separate decision matrices were created for each section of the condition report, which correspond to the six breakout groups and include only that section's proposed indicators. All decision matrices were then added as tabs on a single spreadsheet workbook, allowing experts to view and score all of the proposed indicators in all sections. Participants were encouraged to score the proposed indicators for all sections for which they felt they had expertise. The formulas built into the decision matrix calculated each proposed indicator's score by multiplying the decision criterion weight with the indicator score for that criterion. The products of these were then summed across all criteria for each indicator. This created a score for each expert of how well each indicator fit the weighted criteria.

2.4. Step 4. Select indicators

All participants' scoring were then combined by section; this was achieved by assigning individual top ranks to each indicator based on each expert's scores and then calculating the top five indicators based on the calculated combined highest rank score per section. The combined ranked score method assigns ranks to each expert's scores, so the top score receives the highest rank number. The following steps were used:

1) Sort each individual expert's decision matrix scores of proposed indicators in order from largest to smallest.
2) Assign an integer rank to each proposed indicator according to highest to lowest score (of those that experts scored). If scores tie, average the ranks (e.g. if the proposed indicators "species diversity" and "coral cover" both had a score of 243, they would each be assigned the same rank rather than different descending ordinal integers).
3) Sum all ranks from each expert, per indicator.
4) The highest five sums from each section resulted in the prioritized list of selected indicators.

Thus, the highest rank score integer describes the top proposed indicator candidates (with the highest combined rank scores). The combined rank scoring step was included to remove bias due to difference in criteria weight choices or skipped proposed indicators by individual experts. If two indicators were tied for the fifth overall rank, the section was allowed to have six selected indicators. This approach creates quantitative group consensus from individual scores via qualitative review [4]. After individual rank scoring of proposed indicators by experts in each field by top scores and then combined rank scoring per each section, the prioritized list of selected indicators was reached (Fig. 2).

Long-term data are essential to an ecosystem indicator's ability to assess ecosystem condition and trends. Thus, the availability of long-term data was one of the decision criteria in the decision matrix. Once the indicator suite was selected, long-term data sources were collated to evaluate each indicator and assess the condition of the ecosystem. To aid in this process, each participant was also asked to identify data sources, contacts for potential data, and provide background rationale for their breakout group's proposed indicators. The information on data sources provided from experts was essential for 1) confirming that the top selected indicators could be assessed and 2) streamlining efforts to collect data for the next steps in the indicator evaluation process.

2.5. Step 5. Vet and finalize indicators

After all experts had returned their completed decision matrices and the top scored indicators per section were calculated via rank score, the preliminary list of the top 5–6 (if there were tied scores) selected indicators in each section was sent to all participants for review to determine if the process resulted in any misgivings, misplaced section assignments, missing indicators, and/or counter-intuitive rationale. Any comments and concerns were then addressed, and the list was revisited to ensure it reflected the group consensus. After vetting the selected indicators with all participants, the list was then shared with our management partners at FKNMS for review and to ascertain whether the selected indicators would fit the needs of the sanctuary. A finalized list of selected indicators was distributed to expert participants and sanctuary managers, and assessment of indicators commenced with the collation of data sources (Fig. 2).

To examine potential missing indicators, we removed the data availability criterion from the decision matrix and recalculated the indicator scores (Table 3). This highlighted indicators that have not historically been monitored. However, if scored high enough, this provides justification to establish routine monitoring programs for these indicators.

3. Results

Process facilitators strove to select expert participants with

Table 2
Comprehensive list of all proposed indicators created from the expert workshop in step 2. Top scored and selected indicators are highlighted in bold, with rank scores of selected indicators included.

Sanctuary Waters	Living Resources	Human Activities	Habitat	Ecosystem Services	Maritime Heritage
• **29 Spatial coverage of chl *a* and cyano blooms** • **28 Chl *a* levels on reef tract** • **26.5 Phytoplankton taxonomy** • **21.5 DO** • **16 Fecal indicators in beaches and canal waters** • **15.5 DIN** • **12.5 DIP** • Arsenic and mercury concentrations • CDOM • Changes in circulation patterns (i.e. number of eddies) • Changes in distribution of species to more northern/cooler waters • Changes in pH • Changes in precipitation • Changes in reef habitats (calcification-bioerosion) • Changes in water column temperature profile • Emerging pollutants such as hormonal • Fish kills • Hypersalinity • Increase in shellfish harvesting closures • Light profile • Number of blackwater events • Oil hydrocarbons • pCO2 records as indicator of ocean acidification • Physical risks i.e. wave height • Salinity • Salinity changes • Sea level change • Sea level change • Sea surface temperature change • Soluble Reactive Phosphorus • Total bacteria count • Total carbon • Turbidity levels in reef water column • Underwater noise pollution • Water release events • Wave height and wave period • Wind speed	• **44.5 *Orbicella, Montastrea, A.palmata* and brain coral (reef builders) presence and abundance** • **38 Coral colony counts** • **33 Change in abundance of yellowtail and hogfish** • **28.5 Change in abundance of red and black grouper** • **18 Lionfish change in relative abundance and biomass** • **17.5 Number of species present and abundance of each species via Simpsons Diversity Index** • **17** Diadema antillarum abundance • Change in abundance in number of sea turtle nests (all species) • Change in abundance of stoplight parrotfish • Change in number of fish present at known spawning aggregations (ex. Riley's Hump) Change in number of non-indigenous species • Changes in abundance of nesting birds (i.e. least terns) • Changes in connectivity from Cuba, Gulf of Mexico and Caribbean stocks • Loggerhead sponge habitat presence • Palythoa cover and change in abundance • Permit & Bonefish # of encounters • Queen Conch inshore reproducti-vity • Spotted lobster abundance	• **29 Tourism population trends** • **28 Resident population trends** • **19.5 Land-use percent changes** • **17 Size, type, and number of recreational vessels by registration** • **13 Number of recreational fishing licenses** • **12 Number wastewater management actions implemented via sewer connections** • **11 Fish density and abundance of identified economically important species** • **10.5 Number of commercial fishing trip tickets** • # and size of marinas • # of marine debris clean-ups • # of enforcement actions • Anchor damage • Area and intensity of prop scars by aerial surveys • Bird nesting/roosting sites • Canal dumping incidents • Change in amount of impervious surfaces • Cost of living • Development zoning changes • Dredging and disposal • Fishing density (VMS of boats transiting <4 knots) • Habitat restoration area and extent • Mean transfer efficiency • Mean trophic level of catch and changes in biological community • Number of boat ramp usages • Number of charter fishing licenses • Number of commercial fishing licenses • Number of cruise ship port days • Number of freshwater management decisions implemented • Number of installed mooring buoys • Number of liveaboards without pumpout	• **32 Coral Diversity** • **27 Macroalgae and seagrass species composition and abundance** • **26 Spatial extent and distribution of seagrass beds** • **24 Coral living tissue index** • **19 Spatial cover of mangroves** • **17 Calcification** • **16 Changes in sponge/gorgonian abundance** • Aboveground vs. belowground biomass • Abundance of herbivores • Bioerosion • Bleaching index • Carbonate budget (net erosional vs. accretion) • Coral Size Structure • Disease Prevalence • Light attenuation • Loss from disturbances versus cutting • Macroalgae species composition and abundance • Presence of cyanobacteria • prevalence of prop scars • Ratio of weedy to framework corals • Rugosity and Structure • Seagrass d13C ratios as an indicator of light availability • Seagrass d15N ratios as an indicator of N source and N cycling • seagrass N:P as a measure of nutrient availability • Species distributions • Vegetation cover (canopy height, leaf cover, etc.)	• **26 Commercial fishing landings** • **19 Number of recreational fishing licenses (in state and out of state)** • **19 Mangroves & reef structure as coastal protection** • **19 Satisfaction surveys (i.e. angler)** • **9.5 Total Tourism Value** • **9.5 Housing disruption** • # of boats registered by type • # of outreach efforts • # of boat party zones • # of scientific publications • % born who stay in FK • Aquarium trade captures • Awareness Surveys • Beach visitation • Coastal park visitation • Coastal property value percent increase vs. non-coastal property in Mon-roe County • Commercial effort • Commercial Fishing licenses and boats • commercial value • Curriculum with FKNMS • Diesel toxic additive • Discovery Center visits • Diver/snorkeler Days/ value • Ecotourism index • Fishing engagement & reliance • Florida Keys tags/ mentions on social media • Gentrification index • Hotel occupancy • Live rock aquaculture • Number of Bluestar members • Number of days Monroe County beaches are closed due to poor water quality • Number of non-tourism jobs • Overfishing/overfished index • Proportion of hardened shoreline • Research value via # of research permits • Sanctuary infractions • Sponge fishery • Statistics on visitors purpose for Keys • Reef safe sunscreen use (operators recommending oxybenzone-free, shops carrying oxybenzone free sunscreen)	• **19 Number of resources listed on NRHP** • **19 Number of resources cataloged by NRHP standards** • **16 Number of MAR sites interpreted for public education and outreach** • **13 Level of attendance/ participation in stewardship outreach events (such as heritage awareness seminars, public archaeology, heritage monitoring scouts citizen science)** • **13 Number of potential resources identified from historic record** • **10** Number of lighthouses in Sanctuary in Monroe County eligible for NRHP • Anchoring on/near MAR sites • Fishing on MAR sites • Impacts from marine debris at sites (ex. traps) • Level of awareness of cultural resources • Level of mooring buoy usage (positive effect) • Level of ocean acidification at known MAR sites • Level of sedimentation of MAR • Local knowledge i.e. diver reports of existing MAR • Looting status of sites- via enforcement, anecdotal, resale • Measure of public visitation and awareness by number of Passport stamps for FKNMS shipwreck trail • Number of permitted treasure salvage • Percent of tourists who list MAR as a reason for their visit to county • Storm impacts • Traditional ecological knowledge of number of historical sites • Vessel groundings on MAR sites • Willingness to pay/valuation of maritime heritage

(*continued on next page*)

Table 2 (*continued*)

- Number of regionally targeted domestic fish stocks listed as overfished
- Number of Sanctuary Bluestar members
- Number of vessel groundings
- Recreational fishing effort
- Relevant global geopolitical Issues (e.g. tariffs)
- Sense of place/ cultural identity
- Sewage infrastructure hook-ups
- Trawling fishing activity impact
- Triage for Irma overturning corals
- Turtle abundance and number of nests
- Underwater noise
- Vessel damage

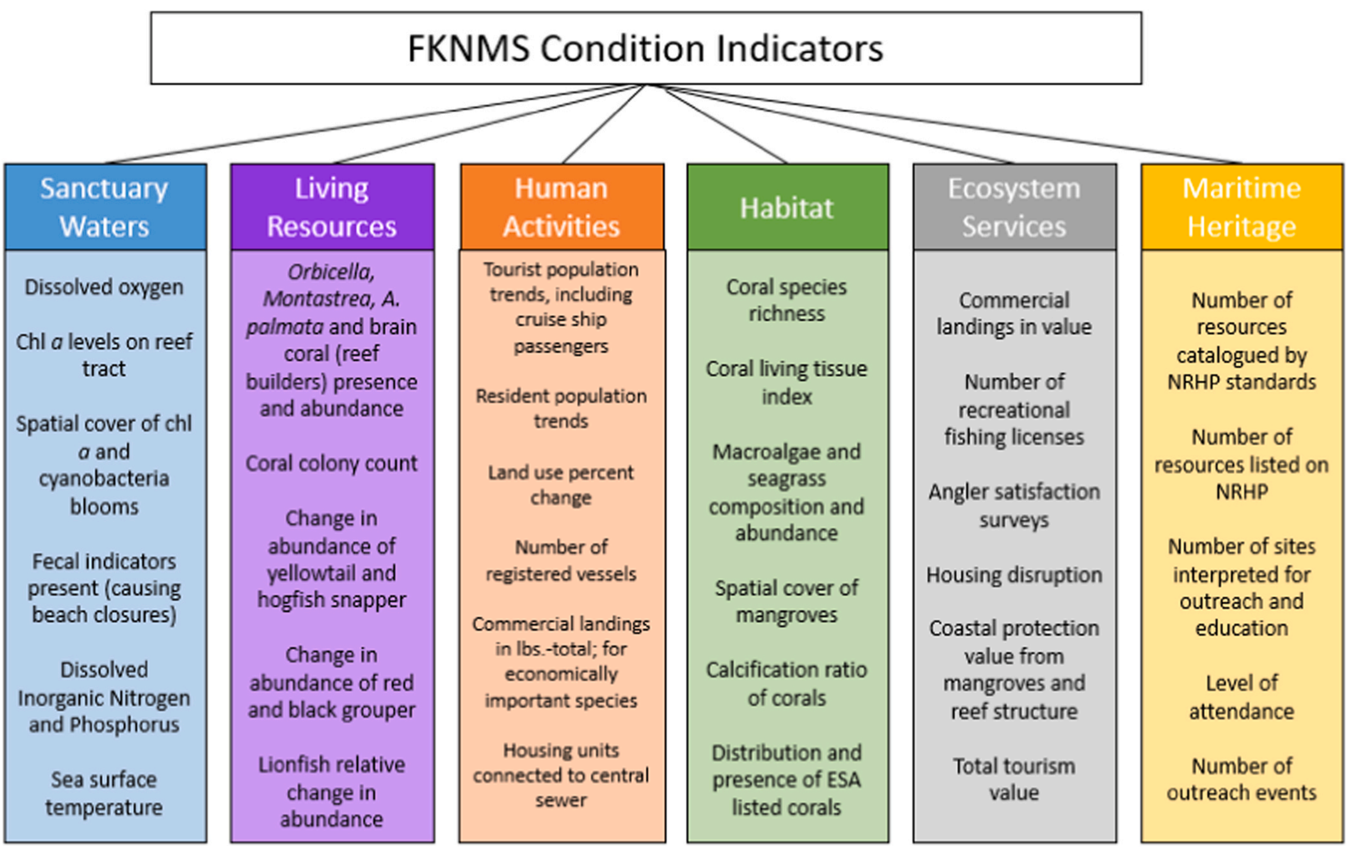

Fig. 2. Final selected indicators for each condition report section.

expansive knowledge of FKNMS. Twenty-eight experts participated in the indicator selection workshop. Participation was based on familiarity of and work in the region, as well as access to large, continuous datasets. Every effort was made to ensure that experts represented both the sections of the condition report and the different habitats of the sanctuary. Those identified experts who were unable to attend were later included remotely via presentations and conference calls, and these remote participants also submitted scored decision matrices. There were six experts included post-workshop via this process, bringing the total number of experts consulted in indicators selection to 34. Sectors with experts participating included federal government research and monitoring, federal fisheries resource managers, state resource agencies, national park managers and scientists, non-governmental environmental resource and fishing experts, academic researchers, human dimensions socio-ecologists, ecosystem modelers, and marine archaeologists.

The group of experts at the workshop agreed with the proposed indicator criteria developed by the project team. Thus, the final decision criteria agreed upon by the group of experts for selecting ecosystem

Table 3

A comparison of top five-scored indicators with and without data availability as a weighted criterion. The indicators that would have scored highest and been in the top five selected indicators per section, had data been available, are indicated in italics.

Sections	Top indicators with all criteria	Combined ranked score	Sections	Top indicators *without* data availability as a criterion	Combined ranked score
Human Activities	Tourist population trends	29	**Human Activities**	Tourist population trends	29
	Resident population trends	28		*Number of freshwater management decisions implemented*	27.5
	Land use percent change	19.5		Resident population trends	26
	Size, type, and number of recreational and commercial vessels by registration	17		Land-use percent changes	21.5
	Recreational fishing via licenses per year	13		*Number of stormwater management actions implemented*	16.5
Maritime Heritage	Number of resources catalogued by NRHP standards	19	**Maritime Heritage**	Number of resources catalogued by NRHP standards	19
	Number of resources listed on NRHP	19		Number of resources listed on NRHP	19
	Number of sites interpreted for public outreach and education	16		Number of sites interpreted for public outreach and education	16
	Level of attendance	13		*Number of potential resources identified from historic record*	15
	Participation in outreach events	13		Participation in outreach events	13
Ecosystem services	Commercial landings	26	**Ecosystem Services**	Commercial landings	23.5
	Recreational fishing licenses (in state and out of state)	19		Coastal protection from mangroves and reef structure	23
	Angler satisfaction surveys *data not actually available, so not used in report	19		Angler satisfaction surveys	20
	Coastal protection from mangroves & reef structure	19		Recreational fishing licenses (in state and out of state)	17
	Housing disruption	9.5		*Resource awareness surveys*	10
	Total tourism value	9.5			
Sanctuary Waters	Spatial cover of chlorophyll *a* and cyanobacterial blooms	29	**Sanctuary Waters**	*Phytoplankton taxonomy*	28.5
	Chlorophyll *a* levels on reef tract	28		Spatial cover of chlorophyll *a* and cyanobacterial blooms	27.5
	Phytoplankton taxonomy*data not available, so not used in report	26.5		Fecal indicators present	22.5
	Dissolved oxygen	21.5		Dissolved oxygen	20.25
	Fecal indicators present	16		Dissolved inorganic nitrogen	12
Living Resources	*Orbicella, Montastrea, A. palmata* and brain coral (reef builders) presence and abundance	44.5	**Living Resources**	*Orbicella, Montastrea, A. palmata* and brain coral (reef builders) presence and abundance	39
	Coral colony counts	38		Coral colony counts	35.5
	Change in abundance of yellowtail and hogfish	33		Change in abundance of yellowtail and hogfish	26
	Change in abundance of red and black grouper	28.5		Change in abundance of red and black grouper	21.5
	Lionfish change in relative abundance and biomass	18		Loggerhead sponge presence	19.5
Habitat	Coral diversity	32	**Habitat**	Coral diversity	26.5
	Coral living tissue index	24		Extent and distribution of seagrass beds	26.5
	Macroalgae and seagrass composition and abundance	27		Coral living tissue index	23
	Spatial cover of mangroves	19		Spatial cover of mangroves	21.5
	Calcification rate	17		Macroalgae and seagrass species composition and abundance	20

indicators to inform sanctuary condition reports were: 1) long-term data availability, 2) importance to the ecosystem and culture, 3) responsiveness to changes in environmental conditions, 4) measurability, 5) relevance to sanctuary condition report questions, and 6) responsiveness to management actions. The indicator workshop resulted in 183 proposed indicators considered by the group (Table 2). This resulted in 35 proposed indicators for sanctuary waters, 18 proposed indicators for living resources, 43 for human activities, 26 for habitat, 39 for ecosystem services, and 22 for maritime heritage.

Twenty-eight experts completed the decision matrix tool. Four experts completed the tool for sanctuary waters, 5 experts completed the tool for living resources, 5 experts completed the tool for habitat, 5 experts completed the tool for human activities, 4 experts completed the tool for ecosystem services, and 5 experts completed the tool for maritime heritage, respectively. Though most experts chose to keep the preset criteria weights discussed in the full group workshop, some adjusted these criteria weights in order to represent criterion they considered most important. Thus, rank averages rather than raw scores were used when combining individual's scored decision matrices in order to remove this potential numerical bias.

The top combined rank averages of each proposed indicator score in each section resulted in a suite of selected indicators. The range of all indicator scores was 0–44.5. The resulting draft list of top-scored indicators of the health and condition of FKNMS is highlighted in bold in Table 2. After vetting by comments and expert review, the finalized list of selected indicators is shown in Fig. 2. Vetting the selected indicators with experts resulted in no changes, but the FKNMS raised concerns regarding whether all habitats were included in the indicators for the habitat section. To address this concern, the top 1–2 scored indicators per habitat type were selected in the habitat section rather than the overall top 5 indicators, regardless of which habitat type they measured.

After vetting, the finalized list of indicators was shared with FKNMS managers and the experts who participated in the process via email and a presentation (Fig. 2). These selected indicators best represent the chosen criteria while providing currently available information on sanctuary condition, in all six sections.

Removing the data availability criterion changed the selected top five indicators in all sections (Table 3). The indicators that would have scored highest and been in the top five selected indicators per section, had data been available, are indicated in italics in Table 3. This work reveals monitoring and data needs in order to best describe the region.

4. Discussion

The application of a criteria-based decision matrix as a decision-making tool is useful in that it draws from both qualitative reasoning and quantitative methods to reach a consensus with a clearly defined, prioritized list of top-selected choices. In other uses of scored matrices by experts, specific indicators have been connected to the delivery of ecosystem services ([3], Oudenhoven 2018). However, the use of indicators here is unique because it features expert weights of criteria, expert-provided potential indicators, and expert ranks of best fit by score to select a comprehensive suite of ecosystem indicators. Moreover, if one of the top-scored indicators cannot be incorporated due to a lack of data availability, it is possible to move down the list and use the next highest scored choice. The process results in a final list of selected indicators that is agreed upon by greater than 30 experts and FKNMS management without being burdened by participant inertia or some voices playing a disproportionate role when collecting expert knowledge.

The described process created a suite of indicators and made a report of ecosystem status for the region possible. Status and trends of the indicator suite were assessed over the time series and over the past five years, using currently available data sources. The status and trend assessments and ecosystem status report will be used to inform the next iteration of the sanctuary's condition report, and are also available for stakeholders to view in an interactive web tool, per request of managers in vetting step [26,27]. The inclusion of indicators in the sanctuary condition report is based upon the work begun in Channel Islands Marine Sanctuary [19], and this process builds upon this previous effort by adding the expert vetting and scoring process to select best indicators to describe sanctuary condition. This process of vetted indicator selection provides needed science information to FKNMS, and addresses many of the concerns raised regarding the lack of science-based indicators in previous condition reports. Upon presentation of the process and resulting indicator suite as well as status and trends to the stakeholders of the Sanctuary Advisory Council, it met favorable reviews.

Other National Marine Sanctuaries, notably Olympic Coast, Cordell Bank, and American Samoa, now plan to implement the developed indicator process described herein. This process will standardize, streamline, and expedite the indicator selection process as the first step to updating condition reports. This adoption proves the process will be a useful tool for other resource managers who seek to select ecosystem indicators to improve management and evaluate decisions by understanding, predicting, and managing for changes and shifts in ecosystem condition. It also suggests resource managers have found this process to be beneficial when selecting scientifically based indicators.

The process piloted and described is time-saving and cost-saving. Prior indicator selection processes often lasted many months to years and required multiple in-person meetings of entire groups of experts (e.g., [16]). This novel approach requires a time commitment from expert participants of only one to two days for an in-person meeting and the time to individually score the electronic copy of the decision matrix. This minimal and concrete time requirement from experts should increase their willingness to participate and broaden participation to marginalized groups and past only those who hold polarized viewpoints from a personal stake in the decision. Thus, the process described should more quickly result in a more scientifically sound selection of indicators from a broader group of experts and at a lower cost than prior selection processes.

The process could be modified by assigning fixed weights to each decision criterion for tighter group standardization if necessary. This would allow for more even comparisons among proposed indicators per established decision criteria, at the expense of losing the ability to collect individual input on the value of each decision criterion. On the other end of this modification option, decision criteria could be fully drafted and selected by in-person group consensus during the in-person workshop. This option was not utilized in the described pilot process as it would require a greater in-person time commitment from experts, nor would it allow for managers to ensure their needs were met and were represented in the criteria selection. The process could also be modified by assigning more weight to specific individual expert's opinion or top stakeholder's representative opinion, if called for in a region or application.

Removing the data criterion highlighted several potential indicators with currently unavailable data, which warrant further consideration in monitoring programs. For sanctuary waters, phytoplankton taxonomy was the highest scored indicator without data availability being considered; whereas chlorophyll *a* levels on the reef tract was the second highest indicator when considering data availability, but not in the top five when data availability was removed (Table 3). Thus, it is likely worth developing a monitoring program that focuses on phytoplankton taxonomy as well as chlorophyll *a* to produce better indicators for sanctuary waters in the future. For human activities, freshwater management actions was in the top five highest scored indicator list without data availability as a criterion, but not included when all criteria were scored. Thus, a regular record available through the years of freshwater management actions would be considered valuable. For ecosystem services, both resident resource awareness surveys and angler satisfaction surveys were ranked as top indicators when data availability was removed as a criterion. This shows a data gap of two indicators considered to be representative of the condition of ecosystem services. For maritime heritage indicators, the number of potential maritime heritage resources identified by the historic record would have been a top scored indicator had information been available. Additional monitoring that provides this data would provide best information on sanctuary condition to managers.

This process can easily be implemented in other regions and for other processes requiring a group consensus to prioritize potential options or suggested alternatives to inform a decision. It uses a simple approach to combine qualitative and quantitative considerations to determine best match of different indicator options via scoring of fitness to specified criteria. A decision criteria matrix could be used to assess how well different identified management scenarios meet the criteria established. This alternate use would harness the goals and potential trade-offs of proposed management actions. This process could also be applied to determine indicators for fisheries management objectives, for ecological restoration projects, for environmental impact monitoring, for alternate marine spatial planning options, and many other ecosystem assessment efforts where environmental management decisions must be made.

5. Conclusions

The described process and tool was piloted to select indicators for the FKNMS condition report. Though ideally all possible parameters would be regularly monitored, this is infeasible and impractical. This process identifies and recommends an indicator suite that best describes the ecosystem condition, thereby guiding the selection of parameters most important to monitor and providing a mechanism to reduce complexity by setting priorities. The selection of these indicators is a key step in the ecosystem-based management approach; however, because of inherent subjectivity and unequal input from minorities, women and early career scientists in group dynamics, the indicator selection, prioritization, and consensus process can be a challenge. This process uses both qualitative and quantitative vetting and selection to result in a prioritized list of best fit indicators to describe the condition of FKNMS resources, ecosystem services, and pressures, while also identifying missing monitoring information that could lead to better indicators. This process is directly transferrable to other national marine sanctuaries, and the process and criteria can be modified to make the selection process applicable to a wide range of ecosystem-based management applications in both marine and terrestrial ecosystems.

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Declaration of interest statement

none.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104489.

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