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Original Article

Towards ecosystem-based management: identifying operational food-web indicators for marine ecosystems

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Modern approaches to Ecosystem-Based Management and sustainable use of marine resources must account for the myriad of pressures (interspecies, human and environmental) affecting marine ecosystems. The network of feeding interactions between co-existing species and populations (food webs) are an important aspect of all marine ecosystems and biodiversity. Here we describe and discuss a process to evaluate the selection of operational food-web indicators for use in evaluating marine ecosystem status. This process brought together experts in food-web ecology, marine ecology, and resource management, to identify available indicators that can be used to inform marine management. Standard evaluation criteria (availability and quality of data, conceptual basis, communicability, relevancy to management) were implemented to identify practical food-web indicators ready for operational use and indicators that hold promise for future use in policy and management. The major attributes of the final suite of operational food-web indicators were structure and functioning. Indicators that represent resilience of the marine ecosystem were less developed. Over 60 potential food-web indicators were evaluated and the final selection of operational food-web indicators includes: the primary production required to sustain a fishery, the productivity of seabirds (or charismatic megafauna), zooplankton indicators, primary productivity, integrated trophic indicators, and the biomass of trophic guilds. More efforts should be made to develop thresholds-based reference points for achieving Good Environmental Status. There is also a need for international collaborations to develop indicators that will facilitate management in marine ecosystems used by multiple countries.

Keywords: ecosystem-based management, good environmental status, indicator selection, integrated ecosystem assessment, marine strategy framework directive.

Introduction

Balancing the long-term maintenance of both biological diversity and human well-being is key to sustainable resource management. As such, ecosystem approaches to resource management that address complex ecological interactions are an essential tool for conservation. While there are number of differing definitions for Ecosystem-Based Management (EBM), there is agreement about the need to move towards a more holistic environmental management approach that recognizes the full array of interactions within an ecosystem (Christensen *et al.*, 1996; Link, 2005, 2010; McLeod *et al.*, 2005). Currently, management actions originating from EBM occur in multiple ecosystems. In terrestrial habitats, EBM has been applied to management a number of times (e.g. Caldwell, 1970; Slocombe, 1998, 1993) and localized EBM efforts for shallow coastal habitats have a also been undertaken (Tallis *et al.*, 2010; Kershner *et al.*, 2011). Globally, a push for EBM in marine ecosystems has been made to balance the tradeoffs inherent in managing these complex ecosystems (Link, 2010). For example, EBM is central to NOAA's Integrated Ecosystem Assessments (IEAs: Levin et al., 2009), Fisheries and Oceans Canada has implemented aspects of EBM in the Canada Oceans Act (Curran *et al.*, 2012), there has been a strong shift towards EBM in Australian fisheries driven by a number of policy directions and initiatives (Smith *et al.*, 2007), the European Union's Marine Strategy Framework Directive (MSFD) has developed an overarching plan to reach and maintain Good Environmental Status (Rogers *et al.*, 2010), and EBM is the recognized mechanism to implement the Convention on the Conservation of Antarctic Living Marine Resources (Constable *et al.*, 2000; Constable, 2011). There is a diverse and widespread effort to continue to better manage marine ecosystems by taking into account multiple pressures, responses, and dynamics simultaneously.

Food webs (the networks formed by the trophic interactions between species in ecological communities) reflect many aspects of ecosystem dynamics. Historically, food web studies developed from simple recordings of biological data through to a phase where patterns in the data were identified and catalogued. Much of the work has since focused on interpreting data and patterns, using either phenomenological or mechanistic models in food webs (Rossberg, 2012). Among representations of food webs in the literature are simple directed graphs (topological webs; e.g. Jordan *et al.*, 2008), flow diagrams (energy budgets; e.g. Polovina, 1984; Ulanowicz, 2004), representations aggregated by size or trophic level, and complex dynamic models (Walters *et al.*, 1997; Link *et al.*, 2005; Piroddi *et al.*, 2015). Depending on the representation, different structural and dynamic properties of food webs emerge from the data. The relationships between these emergent patterns are the subjects of much ongoing research (Rossberg, 2013; de Ruiter *et al.*, 2005; Link *et al.*, 2015).

Ecological indicators are important to EBM because they serve as proxies for several complex ecological processes (e.g. growth dynamics, energy flow) and are representations of ecosystem state (e.g. biodiversity, resilience). In particular, food-web indicators are becoming increasingly important as they represent ecosystem services that concern policy makers and stakeholders. The global uses of these indicators are increasing over time to better inform management of living resources (Jackson *et al.*, 2001; Coll *et al.*, 2008; Levin *et al.*, 2009; Fay *et al.*, 2013; Large *et al.*, 2013; Levin *et al.*, 2014; Large *et al.*, 2015b). For example, food-web indicators have been highlighted as an important component of the Essential Biodiversity Variables, in efforts to evaluate and attain Aichi Biodiversity Targets for 2020 (Convention on Biological Diversity, 2013; Pereira *et al.*, 2013). A critical step in the science-policy process is to not only agree on food-web indicators that are compelling, intuitive, understandable and defensible to all stakeholders, but also capture key food-web states and processes that underlie critical and complex ecosystem dynamics. Important instances of such indicators are those addressing emergent properties of food webs, which are commonly occurring and consistent patterns in trophodynamics of marine ecosystems (Kerr and Dickie, 2001; de Ruiter *et al.*, 2005; ICES, 2013a; Rossberg, 2013; Link *et al.*, 2015). It is important to take into account these properties in selecting food-web indicators in order to develop pragmatic indicators applicable to describe ecosystems at regional or larger scales.

For operational use, primary requirements are that food-web (or for that matter, any) indicators be sensitive to the magnitude and direction of response to underlying attribute/pressure, have a basis in theory, be specific, be responsive at an appropriate time scale, and be cost effective to monitor or to update (Dale and

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Beyeler, 2001; Rice and Rochet, 2005; Link, 2010; Kershner *et al.*, 2011). Those indicators that are well studied and link with emergent properties can address cumulative impacts, integrate dynamic responses to pressures, detect indirect and unintended consequences and can help to evaluate tradeoffs in managing ecosystems. Globally, a set of best-practices is coalescing around indicator selection: a plethora of indicator selection criteria have been developed to identify key facets of indicators (Garcia *et al.*, 2000; Fulton *et al.*, 2005; Institute for European Environmental Policy (IEEP), 2005; Link, 2005; Piet and Jennings, 2005; Rice and Rochet, 2005; Rochet and Rice, 2005; Greenstreet and Rogers, 2006; Methratta and Link, 2006; Samhouri *et al.*, 2009; Shin and Shannon, 2010; Shin *et al.*, 2010a, b; Greenstreet *et al.*, 2011; ICES, 2013a, b; Pereira *et al.*, 2013; Geijzendorffer *et al.*, 2016).

While there have been some efforts to develop operational ecological indicators to evaluate ecosystem status (Pereira *et al.*, 2013; ICES, 2015; Geijzendorffer *et al.*, 2016), the task of selecting specific food-web indicators has been difficult for a number of reasons. Food-web ecology is a rapidly advancing science with new and emerging information and methods (Thompson *et al.*, 2012; Link *et al.*, 2015; Longo *et al.*, 2015). In light of new methodologies in food-web ecology (e.g. stable C and N isotope analysis and molecular genetic techniques to identify prey), historical data are often unsuitable to calculate the necessary metrics to use potential food-web indicators for evaluating ecosystem status. Like many other types of ecological indicators, selection of a specific set of food-web indicators can imply that some aspects of marine food webs are valued more than others. Therefore, a well-balanced selection process for indicators is required that encompasses all currently known properties of marine food webs with the necessary data to be confidently used by both management and stakeholders.

This study aims to provide a list of operational food-web indicators that can be used to quantify the emergent properties of food webs in marine ecosystems. The context for this work was the EU's MSFD need to delineate Good Environmental Status with regard to food webs (Descriptor 4; Rogers et al., 2010; ICES, 2014), but was conducted cognizant of broader potential applications to assess ocean status. Here, we develop a strategy using the best available knowledge from scientific experts and a quantitative methodology for evaluating food-web indicators for implementation in EBM. We also discuss the future development of these indicators for practical use as reference points in management.

Methods

To address ongoing global requirements (Europe, North America and elsewhere), three objectives related to food-web indicators were explored:

- To determine a defined process for selecting food-web indicators.
- To develop a short list of suggested food-web indicators related to management contexts (EBM) in Europe and globally.
- To establish future directions for operationalizing and developing food-web indicators.

This approach led to a two-part set of efforts to (a) identify and evaluate operational food-web indicators that can currently be used and (b) identify food-web indicators that hold promise in the future for management, but that require further development and evaluation. This guidance would allow for increased clarity in selecting food-web indicators coherently within and across regions and lead to more defined response and pressure targets for control rules in EBM. As a part of this broader effort, this project was developed as part of the ICES workshop to develop food-web indicators for operational use in EBM (ICES, 2014). The workshop brought together international experts in food webs, marine ecology, and management to identify appropriate food-web indicators for current use.

Food-web indicators

An initial set of 40 food-web indicators were selected from a list of over 60 candidate indicators presented by the workshop experts. Presentations covered all marine functional groups and all attributes of food webs that were considered necessary for a comprehensive evaluation. Duplicate and technically inappropriate indicators were eliminated from the pool of candidate indicators. The remaining 40 food-web indicators were grouped depending on three main food-web attributes which they addressed: functional indicators linked to energy flow, functional indicators linked to ecosystem resilience and structural indicators linked to diversity and "canary" species (for more detailed descriptions see Supplementary material).

Ranking criteria

A list of 5 criteria and 13 sub-criteria (Table 1) was initially synthesized from a set of criteria determined by previous working groups of experts examining ecological indicators (Kershner *et al.*, 2011; Pereira *et al.*, 2013; ICES, 2015). These criteria were adapted to broadly examine the functionality of the food-web indicators that could be operational within the global context (useful for several countries and regions).

Each indicator was evaluated against the selection criteria and scored as 0, 1 or 2, where 0 = not met, 1 = partly met, and 2 = fully met. A Delphi method (Okoli and Pawlowski, 2004) was used whereby sets of indicators were scored by small groups (of 8–10 experts) based on consensus, following a discussion establishing common understanding of the indicators themselves and how to apply the criteria to the indicators. Each of the 13 sub-criteria was scored equally and no weighting was applied. Scores were presented as percentages of the total score available (maximum score by the number of categories; i.e. $2 \times 13 = 26$). Indicators were ranked by score within the agreed attributes of food webs (Functioning—energy flows, Resilience—ability to recover from perturbation, Structure—species organization). Particular issues or concerns with individual scores were highlighted for subsequent discussions. These were then examined so that all scores were adjusted through consensus-based discussions. This process was used to quantify the usefulness of indicators and to aid in the final selection.

Wider consideration for selecting food-web indicators

In addition to the specific criteria for each food-web indicator, a broader set of features was considered through consensus of the experts involved when evaluating the final recommended suite of indicators. The indicators were categorized into two groups, one set that may be currently implemented and one that holds promise for future development. In some cases, indicators that did not have the highest scores were prioritized based on key

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Table 1. Criteria and sub-criteria used in the selection process for operational food-web indicators.

Criteria	Sub-criteria (issues)	Rationale
Availability of underlying data	Existing and ongoing data	Indicators are supported by current or planned monitoring programmes that provide the data necessary to derive the indicator. Ideal monitoring programmes should have a time series capable of supporting baselines and reference point setting. Data should be collected on multiple sequential occasions using consistent protocols
	Relevant spatial coverage	Data should be derived from an appropriate proportion of the regional sea, at appropriate spatial resolution and sampling design, to which the indicator will apply
	Relevant temporal coverage	Data should be collected at appropriate sampling frequency and for an appropriate extent of time relevant to the time scale of the process or attribute the indicator describes.
Quality of underlying data	Indicators should be technically rigorous	Indicators should ideally be easily and accurately determined using technically feasible and quality assured methods
	Reflects changes in ecosystem component that are caused by variation in any specified manageable pressures	The indicator reflects change in the state of an ecological component that is caused by specific significant manageable pressures (e.g. fishing mortality, habitat destruction). The indicator should, therefore, respond sensitively to particular changes in pressure. The response should based on theoretical or empirical knowledge, thus reflecting the effect of change in pressure on the ecosystem component in question; signal to noise ratio should be high. Ideally the pressure–state relationship should be defined under both the disturbance and recovery phases
	Magnitude, direction and variance of indicator is estimable	The indicator should exhibit a predictable direction, exhibit clear sense of magnitude of any change, and estimates of precision should allow for detection of trends or distinct locales—requiring that some measure of sampling error or variance estimator is available
Conceptual basis	Scientific credibility	Scientific, peer-reviewed findings should underpin the assertion that the indicator provides a true representation of process, and variation thereof, for the ecosystem attribute being examined
	Associated with key processes	The link between the indicator and a process that is essential to food web functioning should be clear and established, based on our current understanding of trophic dynamics
	Unambiguous	The indicator responds unambiguously to a pressure
Communication	Comprehensible	Indicators should be interpretable in a way that is easily understandable by policy-makers and other non-scientists (e.g. stakeholders) alike, and the consequences of variation in the indicator should be easy to communicate
Management	Relevant to management	Indicator links directly to mandated management needs, and ideally to management response. The relationship between human activity and resulting pressure on the ecological component is clearly understood
	Management thresholds targets are estimable	Clear targets that meet appropriate target criteria (absolute values or trend directions) for the indicator can be specified that reflect management objectives, such as achieving GES. Ideally control rules can be developed
	Cost-effectiveness	Sampling, measuring, processing, analysing indicator data, and reporting assessment outcomes should make effective use of limited financial resources

considerations and selected for the final suite of food-web indicators. The key considerations were:

Relative ranks within the major food-web indicator attributes informed the choice of indicators, but were not adhered to in a strictly quantitative manner.

Coverage of all functional groups found within a food web. Recognizing that much indicator development has occurred for upper trophic level contexts, we ensured that lower trophic level taxa were not omitted, even though as a group they may have scored lower than more commonly or routinely monitored upper trophic levels.

Major indicator attributes (*structure, function*, *and resilience*) were as well represented as possible to ensure that important facets of food webs were included.

Current operability was effectively based on an *ad hoc* review (or weighting) of operability issues related to data availability, management relevance and existence of baselines, targets, or related reference points, although they were selection criteria, were deemed critical enough to warrant additional consideration.

Links to other indicator uses were considered to ensure that food-web indicators that are unique to describing food webs were emphasized. Where indicators had strong connections to other indicator uses (e.g. biodiversity, fisheries, eutrophication, and sea floor integrity), they were discounted in order to specifically examine indicators tied to food webs.

Results

Within each attribute, indicators tended to cluster into groups with similar underlying ecological theory. When selecting priority indicators for further development, it was, therefore, considered necessary to review the full list of indicators and ensure that those that clustered together, but with lower scores, were also taken into consideration to maintain a diversity of indicator formulations.

The rank scores were obtained from the unweighted sum of all 13 evaluation sub-criteria (Table 2). When the evaluation was rerun separately using only the first six sub-criteria in Table 1 (linked to practical aspects of indicator measurement), and the

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Table 2. Assessment of food-web indicators for indicators against the criteria in Table 1.

	Food-web indicator	Availability	Quality	Conceptual	Communication	Management	Score	Percent	Other indicator uses
Energy Flow indicators	Seabird breeding success	6	3	6	2	5	22	85	Biological diversity
	Mean weight at age of predatory fish species from data	4	5	5	2	5	21	81	Fisheries
	Total mortality	4	5	4	1	5	19	73	Fisheries
	Productivity of key predators	6	3	4	1	4	18	69	
	Primary production required to support fisheries	4	3	6	0	5	18	69	Fisheries, biological diversity
	Productive pelagic habitat index	6	4	4	1	3	18	69	Eutrophication, fisheries, biological diversity
	Ecosystem exploitation	5	3	2	1	5	16	62	Fisheries
	Community condition	3	5	3	2	3	16	62	Fisheries
	Mean trophic level of catch	4	4	2	1	4	15	58	Fisheries
	Marine trophic index of the community	4	3	4	1	3	15	58	
	Mean trophic level of the community	4	3	4	1	3	15	58	
	Disturbance index	4	3	4	1	2	14	54	
	Loss in secondary production index	4	3	4	0	3	14	54	Fisheries
	Cumulative distribution of biomass assessment	4	3	4	0	3	14	54	Fisheries
	Trophic balance index	4	2	3	0	4	13	50	
	Mean transfer efficiency for a given trophic level or size	3	2	4	0	1	10	38	
	Finn cycling index	3	1	4	0	1	9	35	Fisheries
Ecosystem resilience indicators	Mean trophic links per species	3	2	4	1	2	12	46	Biological diversity
	Ecological network analysis derived indicators	4	1	4	1	2	12	46	
	Gini-Simpson dietary diversity index	3	2	4	1	1	11	42	
	Herbivory to detritivory ratio	3	1	4	1	1	10	38	
	Ecological network indices of ecosystem status and change	4	1	4	0	1	10	38	
	System omnivory index	3	1	2	0	1	7	27	
Structural indicators	Guild surplus production models	6	6	6	1	6	25	96	Fisheries
	Large fish indicator	6	6	5	2	6	25	96	Fisheries
	Total biomass of small fish	6	5	5	2	5	23	88	Fisheries
	Proportion of predatory fish	6	3	5	2	6	22	85	Biological diversity, Fisheries
	Mean length of surveyed community	6	6	4	2	4	22	85	Biological diversity, Fisheries
	Pelagic to demersal ratio	6	5	4	2	4	21	81	Fisheries, eutrophication
	Guild level biomass	4	3	5	2	6	20	77	Biological diversity, Fisheries
	Lifeform-based indicator for the pelagic habitat	6	5	4	1	4	20	77	Biological diversity, eutrophication, sea-floor integrity
	Region-specific indicators of abundance and spatial distribution	6	3	4	1	5	19	73	Biological diversity, fisheries,
	Scavenger biomass	3	5	5	1	5	19	73	Biological diversity, sea-floor integrity
	Geometric mean abundance of seabirds	6	3	5	1	4	19	73	Biological diversity
	Size spectra slope	6	4	4	1	4	19	73	Biological diversity, fisheries, sea-floor integrity
	Fish biomass to benthos biomass from models	4	3	4	2	4	17	65	Biological diversity, fisheries, Sea-floor integrity
	Zooplankton spatial distribution and total biomass	4	4	3	2	4	17	65	Biological diversity, eutrophication
	Zooplankton mean size	4	4	3	2	4	17	65	Biological diversity, eutrophication
	Gini–Simpson diversity index	6	2	2	0	4	14	54	Biological diversity
	Species richness index	6	2	2	2	2	14	54	Biological diversity

A maximum score for availability of data= 6, quality of data = 6, conceptual = 6, communication = 2, management = 6 (maximum score is 26).

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next seven criteria (linked to aspects of indicator implementation), there was relatively little difference in the final overall outcome. This suggests that the rank scores were robust to variability in criteria selection and were minimally influenced by single criteria evaluations.

Energy flow indicators

A relatively large number of indicators had clear links to functional aspects of food webs (Table 2). Production or biomass ratios for various parts of the food web detect gross structural changes in the energy flow through a food web which may have been caused by, for example, harvesting of key species, seabird breeding success, or disruption of distributional overlap between predators and prey through climatic factors.

Total mortality Z (Fishing mortality + natural mortality or production to biomass ratio), is commonly used in the ecosystem modelling community (Pauly et al., 2000; Christensen and Pauly, 2008). Despite the relatively high score, this was not the most easily interpretable indicator of food web functioning. This was evident in the low score for the communication criteria (Table 2). Ecosystem exploitation was considered useful to describe the harvesting pattern of exploited ecosystems. It is an indicator of the pressure of the fisheries on the food web.

Primary Production Required (PPR) to sustain a fishery has a solid conceptual basis (Pauly and Christensen, 1995). However, the difficulty of explaining the concept to the lay public contributed to a moderate score for this indicator. Moreover, this indicator does require estimates of transfer efficiency (TE), which is generally assumed to be 10–15% between trophic levels. Note that indicators of transfer efficiency themselves were not selected as indicators for use immediately due to the lack systematic TE measurements. Monitoring intermediate marine productivity and chlorophyll *a* fronts by satellite using remote observation was considered effective to estimate indicators of energy-flow in food webs.

Four fairly similar indicators based on trophic level were evaluated (the mean trophic level of the catch, the mean trophic index of the fish community, mean trophic links per species and the Trophic Balance Index). Each has a slightly different formulation, but all require good quality and regularly updated data on dietary relationships, time series of survey catch, or landings from broad regional seas to avoid local population or fleet effects, and accurate, agreed upon and regularly updated assessments of the trophic levels of the ingested food. Similarly, the Trophic Balance Index, describing the fishing pattern of local métiers, can be useful in the context of assessing food web effects of fisheries harvesting, but has limited application for other pressures.

Low scores allocated to indicators such as the disturbance index, loss in production index, mean transfer efficiency and Finn Cycling Index were due to uncertainty over the quality of the technical assessment (data needs and rigor) and the likely ease of implementation. However, some of the indicators may warrant further investigation.

Resilience indicators

It was interesting to note that the six indicators that had a link to resilience of the food web were generally scored lower than many other indicators (Table 2). This may be because they are more conceptually complex. The top three in this category, the mean number of trophic links per species, Ecological Network Analysis derived indicators, and the Gini-Simpson dietary diversity index, all held promise as food-web indicators, but the group of experts felt that these would not be recommended as suitable for implementation in the short-term. The conceptual and technical difficulty of measuring food-web resilience and ability to recover from perturbation partly explains the low scores allocated to the assessment criteria in the area of cost-effectiveness of data gathering, although they all have strong support in the literature.

The indicators for the resilience attribute that scored poorly (Herbivory:Detritivory Ratio, Ecological Network Indices, System Omnivory Indices) will take more time to develop. The complexity of their formulation also suggests that, even if further developed, they may be difficult to explain in a management context. More importantly, these indicators need regular diet time series data encompassing the entire food web, which have not been made widely available even to support applied multispecies fishery assessments.

Structural indicators

Several indicators in this category obtained relatively high scores, suggesting that managers may want to use these indicators to help interpret patterns observed particularly at higher trophic levels. Another important consideration is the role of aggregated sets of structural indicators, such as those related to phytoplankton, zooplankton, forage fish, scavengers, and birds, which together have important implications for food-web resilience (e.g. low or high biodiversity) as well as structure of the individual components (i.e. species). Many structural indicators are describing the same ecosystem components in multiple ways (Table 2) and due to the multi-faceted uses of these indicators (in addition to characterizing food webs) the data are likely to be collected and available.

Higher-scoring indicators were those which informed trends in absolute biomass, production, or ratios of both, for a number of guild-level ecosystem components, especially higher trophic level predators. For those structural indicators that aggregate across multiple components, it was generally thought preferable to have indicators comprising absolute values rather than ratios, as these data would be necessary anyway to interpret ratio metrics. It is, however, recognized that when comparing across ecosystems, examining trends, and relative measures are recommended. Some of these abundance-related indicators may be given a higher priority if they are also useful for informing an aspect of food-web resilience. For example, both the Gini-Simpson diversity indices for small and large fish and the Species Richness Index were thought to be potentially useful for assessing food web resilience.

Suggested food-web indicators

The following indicators are the refined set of food-web indicators (Table 3) recommended for current use based on the selection criteria (Table 1) and accounting for the wider considerations in the selection process (Table 2).

Guild level biomass (and production)

Guild-level biomasses and production address structural attributes of food webs, and can also serve as proxies for functioning (Zador *et al.*, 2016). It was noted that the typical use of this type of indicator has been for fishes, but if feasible this indicator should include multiple guilds across all trophic levels, such as

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Table 3. Suggested food-web indicator groups and specific indicators.

Suggested indicator groups	Indicators	Ecosystem attribute
Guild level biomass (and production)	• Total biomass of small fish • Biomass of trophic guilds	Structural/functional
Primary Production Required to sustain fishery (PPR)	Primary production required to support fishery	Functional
Seabird (charismatic megafauna) productivity	Seabird breeding success	Functional/resilience
Zooplankton size biomass index	Zooplankton spatial distribution and total biomass	Structural
Integrated trophic indicators	• Mean trophic level of catch • Marine trophic index of the community • Mean trophic level of the community • Mean trophic links per species	Structural/Resilience

primary producers, zooplankton, benthos, and charismatic megafauna, beyond just fish or upper tropic levels. The guilds should be determined as appropriate for the taxa in a given regional sea.

PPR to sustain a fishery

This addresses the functioning attribute of food webs and is a measure of the ecological footprint of a fishery. However, this metric can (and often does) integrate a wide range of removals from the food web. Derivatives of this food-web indicator could, where feasible, be contrasted to measures of primary production to ensure that it is directly appraised against field data. Satellite imagery makes estimates of primary production widely available (given the usual caveats of remotely sensed data), and typical landings and associated data are also widely available, making PPR more integrative and feasible than is often perceived.

Seabird (charismatic megafauna) productivity

The breeding success of seabirds addresses the structural and functional attribute of a food web and can also serve as a proxy for resilience. Although particular to seabirds, especially breeding success/chicks per pair, it was recognized that seabirds may not be prominent or important in all regional seas. A similar productivity indicator could be calculated for marine mammal taxa (i.e. pup production rates).

Zooplankton size biomass index

This indicator addresses both structural and functional attributes of food webs in terms of energy transfer in pelagic habitats. Although indicators associated with this taxonomic group were often ranked lower, they represent an important part of the food web—the link between primary production at lower trophic level and upper trophic level consumption and growth.

Integrated trophic indicators (mean trophic level, mean size)

Trophic indicators address both structural and resilience attributes of food webs. It was critical to include an explicitly integrative measure that provided some view of the overall system and did not focus on only certain facets of it. There are many possible indicators in this category from which to choose, such as mean trophic level, mean, or proportion at size of the community (depending upon abundance) and trophic data availability in a given regional sea.

Indicators for development

Food-web indicators that were recommended for future development were Ecological Network Analysis indicators, the Gini–Simpson dietary diversity index and condition indicators. These indicators lacked the development to be considered currently useful for management, but all were determined to be representative of multiple aspects of the food-web (integrated food-web perspective; e.g. Heymans *et al.*, 2014), and are currently used in modelling studies (e.g. Heymans *et al.*, 2007). Some indicators that were suggested to be currently operational (marine trophic level indicators, primary producers and zooplankton indicators) were also thought to require more development to fully meet their potential and range as indicators for food-web and other indicator uses.

Discussion

The five food-web indicator groups recommended from this process cover important facets of food webs, particularly addressing structural, functional, and resilient features of marine food webs (Table 3; Polis and Strong, 1996; Thompson et al., 2012; Jennings and Collingridge, 2015). It is likely that multiple indicators are needed to track the multiple attributes that comprise food webs and delineation of Good Environmental Status (Rice and Rochet, 2005; Mallory *et al.*, 2010; Large *et al.*, 2015a, b) of which these five candidates are suitable options. All the five food-web indicator groups proposed here are generally applicable in terms of capturing the main facets of food-web dynamics (Methratta and Link, 2006; Shannon *et al.*, 2009; ICES, 2014) and readily link to known behaviours of food webs. Many of these indicators are broad enough in context to be applied across many marine ecosystems (coastal, temperate, arctic, tropical, etc.; Fulton et al., 2005; Parsons et al., 2008; Coll and Libralato, 2012; Zador et al., 2014; Hayes et al., 2015).

The five proposed indicator groups may not all have widely and consistently monitored data available to sufficiently calculate the metrics. Although important to track lower-trophic level dynamics and linkages to upper-trophic level taxa, the zooplankton indicator may not have widely collected data for all regional seas with the same spatial and time frequency nor be as easily interpreted, given the high seasonality of these taxa (Vargas *et al.*, 2006; Pershing *et al.*, 2005; Stige *et al.*, 2014). The integrated trophic indicators hold equal promise, but similarly may not always have measures of trophic level or equivalent information (Rossberg *et al.*, 2006; Gaichas *et al.*, 2012; Pranovi *et al.*, 2012; Hornborg *et al.*, 2013). Justifiable assumptions regarding trophic level, using common databases on trophic ecology of taxa (e.g. fishbase; Froese, 1992; Froese and Pauly, 2013), may provide a means to more readily calculate these indicators in the absence of local trophic data. Size-based integrated indicators are less demanding on data and show clearer responses in food webs

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(Greenstreet *et al.*, 2011; Shephard *et al.*, 2011; Fung *et al.*, 2013; Engelhard *et al.*, 2015). These size-based indicators, specifically the Large Fish Indicator, scored high; however, given that these are useful indicators primarily for describing the impacts of fisheries, it was not part of the final selection of indicators recommended for describing changes in food webs. The salient point is that there are well-studied extant indicators able to track and delineate environmental status in marine food webs (Houle *et al.*, 2012). These were explored in the MSFD Good Environmental Status context (ICES, 2008, 2013b; Shephard *et al.*, 2014; ICES, 2015), but are generally applicable for marine conservation considerations.

Regardless of the specific indicator set chosen, EBM requires a replicable, transparent, defendable, and clear process for indicator selection (Dale and Beyeler, 2001; Link, 2010; Shin *et al.*, 2010a). The process demonstrated here is broadly applicable in a wide array of conservation situations and it is as important as the outcomes. It is essentially a multi-criteria decision analysis (Mendoza and Martins, 2006; Pereira *et al.*, 2013), whereby the selection of indicators is agreed-to before use in tracking ecosystem status. The criteria for indicator assessment used here are sufficiently robust to be applied in a range of situations, with one of the five main criteria specifically evaluating how useful a given indicator is to management. These criteria are converging in the marine management context, but can be readily used in other forms of natural resource management (e.g. terrestrial, estuarine). Due to the well-documented quantitative and qualitative evaluation in the selection process, there is a high level of confidence in the choice of the final set of indicators. This process allows for regular updates and inclusion of novel information (Curtin and Prellezo, 2010; Kershner *et al.*, 2011) while maintaining a record of how selections are made. This process is general enough to be used regardless of the type of ecosystem and conservation issue being considered, as long as the criteria are agreed upon *a priori* (Mendoza and Martins, 2006; Espinosa-Romero *et al.*, 2011). Although similar selection processes have a wide history of use in conservation (Mendoza and Martins, 2006), it could be even more widely and rigorously applied.

Based on the evaluation process, the food-web indicators selected in this study can offer some guidance towards possible management actions. For example, both higher-trophic (seabird and charismatic megafauna productivity) and lower-trophic indicators (PPR and zooplankton index) are reflective of bottom-up processes viewed from opposing ends of the food web (Cury *et al.*, 2011; Einoder, 2009; Hilting *et al.*, 2013). PPR is an integrative indicator that represents the amount of primary productivity to sustain a fishery, and offers a means to compare energy requirements across different fisheries (Gascuel *et al.*, 2005; Chassot *et al.*, 2010). Seabird productivity is an indicator of food availability (forage fish) and can also be sensitive to contaminants and environmental pollutants (Mallory *et al.*, 2010). Direct management actions to influence these indicators could be either top-down control rules aimed at relieving fishing pressure on lower-trophic species or bottom-up policies directed to improve water quality or habitat, which may also include improved management at land-sea interfaces (Furness and Camphuysen, 1997; Kendall *et al.*, 2010; King and Baker, 2010; Mallory *et al.*, 2010; Teichert *et al.*, 2015). Specific management actions will be dependent on regional circumstances and the responses of the indicators to local pressures, but by using common indicators it will be possible to compare ecosystem status between regions and to help management at all levels (from regional to national to international) and to make effective decisions to improve the world's oceans.

This proposed set of candidate indicators is a start towards operationalizing the delineation of marine ecosystem status, but may require a few further steps before becoming fully operational. Food-web indicators may be interesting scientifically and relevant for management, but if they cannot inform management actions directly they certainly have less utility. Establishing decision criteria that trigger management actions for EBM requires an understanding of how pressure variables influence indicators, as well as the level of a particular pressure at which significant changes in ecosystem structure or function appear (Link, 2002a; Groffman *et al.*, 2006; Blanchard *et al.*, 2010; Coll *et al.*, 2010; Link, 2010; Samhouri *et al.*, 2010). Such thresholds have been explored with a wide range of analytical methods, such as cumulative sums (CUSUM; Hinkley, 1970), sequential t-test (STARS; Rodinov, 2004), empirical fluctuation processes (Zeileis and Kleiber, 2005), and significant zero crossings of piecewise regression models (Chaudihuri and Marron, 1999; Toms and Lesperance, 2003; Sonderegger *et al.*, 2008; Samhouri *et al.*, 2010, 2012; Toms and Villard, 2015) or generalized additive models (Large *et al.*, 2013), all to identify the level of pressure that results in a significant indicator response (Andersen *et al.*, 2009). These univariate relationships are useful for establishing decision criteria (Samhouri *et al.*, 2010; Fay *et al.*, 2013; Large *et al.*, 2013); however, they do not fully account for multiple pressures that likely interact and occur concurrently. An assessment of ecosystem status based on suites of indicators will be more powerful. Using multiple indicators to evaluate ecosystems will help to avoid the possibility of misinterpretation which can occur when indicators are evaluated in isolation (Rice and Rochet, 2005; Coll and Libralato, 2012; Shin and Shannon, 2010; Shin *et al.*, 2012; Longo *et al.*, 2015). Multivariate approaches exist to detect thresholds, including translating indicator response into a surface dependent on multiple pressures (i.e., fishing and environmental pressure; Scott et al., 2006; Frederiksen et al., 2007; Large et al., 2015a), multivariate ordination methods (Baker and King, 2010; King and Baker, 2010) and extensions of regression tree and gradient forest analyses (Liaw and Wiener, 2002; Prasad *et al.*, 2006; Ellis *et al.*, 2008; Pitcher *et al.*, 2012; Baker and Hollowed, 2014; Large *et al.*, 2015a). Understanding how multiple pressure variables concurrently influence ecosystem status, as evinced by thresholds in indicators, will help to further operationalize these indicators as reference points for management.

Another critical step in operationalizing food-web indicators for management is to define and determine specific management objectives regarding the ecosystem attributes the indicators represent. Avoiding quantitative threshold points along pressure gradients are useful to avert regime shifts (Samhouri *et al.*, 2010; Large *et al.*, 2013, 2015a, b). Rossberg *et al.* (2017) developed a quantitative method for setting targets for indicators that considers societal needs and ecosystem sustainability. Setting such management objectives will differ between countries or groups of countries and will require specific considerations set by managers and stakeholders.

When assessing the status of marine ecosystems, it is important to adequately characterize the food web (Link, 2002b; Branch *et al.*, 2010; Thompson *et al.*, 2012). Certainly there are other aspects of marine ecosystem status, a fact which is explicitly acknowledged in the MSFD. Yet, too often the development of

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marine indicators neglect consideration of food webs (Hayes *et al.*, 2015). Understanding food webs in ecosystems is paramount because they are able to unify ecological sub-disciplines (behaviour, dispersal, physiology, thermodynamics, etc.) and to examine interactions among guilds (Polis and Strong, 1996; Thompson *et al.*, 2012; Rossberg, 2013). Food webs are able to integrate species-based and functional-based approaches to examine biomass distributions and energetic flows within systems. Another key aspect of ecosystems that is encompassed by food webs is resilience. It is thought that a resilient system reacts only weakly to pressure, but resilience might be lost with increasing pressures, leading to rapid changes to different states or regimes. Such transition is thus the result of an accumulation of the disturbing effects of pressures (Gunderson, 2000; Folke *et al.*, 2004; Sasaki *et al.*, 2015). Additionally, ecosystems may exhibit legacy effects of earlier pressures (Hughes *et al.*, 2005; Folke, 2006). Despite the difficulty in studying food webs in their entirety (including large data requirements and advanced computational abilities), emergent trends have been established in food-web ecology at both the community (Fredriksen, 2003; Neira *et al.*, 2009) and ecosystem level (Link *et al.*, 2015).

Conclusion

An important aim of EBM is to balance between multiple, often conflicting objectives. How management actions take shape depends on all user groups involved, including stakeholders, indigenous communities, fishers, tourists, NGOs, etc. (Branch *et al.*, 2006; Marasco *et al.*, 2007; Link, 2010). The most successful implementation of EBM will be one where user groups are equally engaged, can agree on a set objectives, work towards common economic-social-conservation management goals and ultimately overcome inertia in the decision making process (Arkema *et al.*, 2006; Leslie and McLeod, 2007; Pitcher *et al.*, 2009; deReynier *et al.*, 2010; Link, 2010; Espinosa-Romero *et al.*, 2011; Röckmann *et al.*, 2015; Sandström *et al.*, 2015). The set of indicators proposed in this study is an example of how such information can be used to more fully implement EBM by evaluating one facet of marine ecosystem objectives associated with food webs. More so, the process described here is an important means to explore the management and policy tradeoffs not only in selecting these indicators but also the underlying objectives and dynamics that each represents.

Ecological indicators for the conservation of biodiversity (including food-web indicators) are useful to summarize complex information concerning marine ecosystem status (Cury and Christensen, 2005; Fulton *et al.*, 2005; Dulvy *et al.*, 2006; Methratta and Link, 2006; Pereira *et al.*, 2013; Hayes *et al.*, 2015; ICES, 2015; Geijzendorffer *et al.*, 2016). Clearly defined, consistent metrics at the global scale can provide management in multiple countries with the tools to make EBM more operational (Leslie and McLeod, 2007; Smith *et al.*, 2007; Lester *et al.*, 2010; Link, 2010; Thrush and Dayton, 2010; Link *et al.*, 2011). As management efforts continue to implement EBM to meet conservation objectives, having a suite of indicators, a process to select them and ensuring that they map to clear management needs will remain increasingly important.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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