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Report of the Workshop to develop recommendations for potentially useful Food Web Indicators (WKFooWI)

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Executive summary

This workshop brought together international experts in food webs, marine ecology, and management, to identify appropriate Food Web Indicators. The work contributed to ongoing requirements in Europe, North America and elsewhere to manage marine ecosystems in a holistic manner. The workshop built on progress already made to support Descriptor 4 (Food Webs) through a joint JRC/ DG ENV task force, and guidance from the European Commission on provisional guidelines for setting targets and defining indicators. The workshop applied standard evaluation criteria to progress the (i) identification and evaluation of practical food web indicators (FooWIs) ready for operational use, and (ii) identification of FooWIs that hold reasonable promise in the near- to medium term future but that require further development. It was recognized that structure and functioning of food webs were the major attributes for which indicators were required, following earlier guidance by the Commission. In addition, WKFooWI emphasized that resilience of food webs was a key aspect of ecosystem behaviour and environmental status and so was treated as an additional attribute. Over 60 potential food web indicators were evaluated in these three categories. WKFooWI concluded that in the short term for the specific Descriptor 4 context, indicators on; the primary production required to sustain a fishery, the productivity of seabirds (or similar charismatic megafauna), zooplankton indicators based on community biomass, size structure and productivity, integrated trophic indicators (including e.g. mean trophic level, mean size, etc), and the biomass of trophic guilds, should be considered for application at a Regional Seas scale. Suggestions were also made for areas for further development in the medium-term future (i.e. 2–3 years). It was emphasized that more efforts should be made to encourage a greater level of integration in the development of indicators elsewhere in the Marine Strategy Framework Directive and Regional Seas Conventions, in order to encourage more coherence at a regional seas scale.

1 Introduction and Expectations

1.1 Background and Rationale for WKFooWI

Modern approaches to sustainable use of marine resources must account for the myriad impacts (exploitation, deposition, disruption, and other stressors) accrued from utilizing the goods and services from the entire ecosystem. An important aspect of any marine ecosystem is its food web, i.e. the network of feeding interactions between co-existing species and populations. This workshop on Food Web Indicators (WKFooWI) brought together experts in food webs, marine ecology, and management, to identify available indicators that can be used to inform marine management.

There is a well-established need to use indicators of food webs that reflect characteristics of energy flow, resilience, structure and functioning in the management of marine ecosystems, and the management of the components in those marine ecosystems (Shin *et al*., 2010, 2012, Link 2005, Rice and Rochet 2005, Fulton 2005, etc.). Food web indicators better and more directly represent key features of marine ecosystems and living marine resources that are often missed with less integrative measures. As such they can provide useful information pertaining to Good Environmental Status.

Such foodweb indicators are called for by, among others, the European Commission's Marine Strategy Framework Directive (MSFD), an overarching plan to reach and maintain Good Environmental Status (GES) for all marine waters bordering the EU. The MSFD characterises the status of the marine environment into 11 Descriptors. One of these, D4, addresses specifically *Elements of marine food webs*. Other Descriptors, such as D1 (*Biological diversity*), D3 (*Population of commercial fish / shell fish*), D5 (*Eutrophication*), D6 (*Sea floor integrity*), cover additional information relevant to interpreting the status of foodweb. Building on the work of a joint JRC/ DG ENV task force (Rogers *et al*. 2010), a Decision by the European Commission provided provisional guidelines for setting targets and defining indicators for GES under D4 (2010/477/EU), understanding that these need further development as experience with food web indicators (FooWI) increases.

The workshop used the best available knowledge from ICES science experts to inform and advise the Commission and EU member states on options available to implement Descriptor 4 of the MSFD. It was recognized that an evaluation of food web indicators also had broader potential application.

There were some general and important indicator-related principles that informed the workshop deliberations. These have originated from observations, simulations, and studies from a variety of other, diverse efforts that have evaluated indicators, including:

- The need to have a suite of indicators, and not just the "one" indicator
- The need to have clear criteria for selecting indicators
- The need to have clear objectives for why indicators shall be developed and used
- The need to have clear venues for evaluating, vetting and referencing indicators
- The need to have clear "clients" who will use the indicators and are asking for them

1.2 A brief Primer on Food Webs

Food webs are the networks formed by the trophic (feeding) interactions between species in ecological communities. The study of food webs developed from a science that simply recorded data, through a phase of cataloguing and identifying patterns in the data, and then moved towards interpreting data and patterns, first in terms of phenomenological models and later in terms of general ecological mechanizms and accounting of the transfer of mass and energy among biota (Bersier 2007, Rossberg 2012). Key concepts in foodweb studies are *consumer,* denoting any species feeding on other species, *producer,* often denoting any species which is not a consumer, *resource,* usually a species being fed on by a consumer, and *trophic link*, a direct consumer-resource interaction. A *food chain* is sequence of successive consumer-resource pairs, and the *trophic level* of a species is defined as 1 plus the mean length of all food chains linking it to producers, weighted by biomass flow (Levin 1980). Among representations of food webs in the literature are simple directed graphs (topological webs), flow diagrams (energy budgets), representations aggregated by size or trophic level, and complex dynamic models (biodemographic webs). 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 (de Ruiter *et al*., 2005, Duffy *et al*. 2007, Thompson *et al*. 2012, Rossberg 2013).

Key attributes of food webs are structure, functioning and resilience and these are used here to guide the selection of food web indicators.

1.3 Emergent properties of food webs

Emergent properties are those that can be predicted without understanding in detail the complexities of a food web. This predictability is reflected in the existence of simplified models or representations of food webs addressing specific emergent properties (ICES, WGECO 2012). Examples are representations of food webs as food chains passing energy and biomass from lower to higher trophic levels, representations in form of dynamically interacting aggregated groups of species, representations as graphs with arrows (feeding interaction) linking nodes (species), where a small number of top predators are supported by increasing numbers of species at lower trophic levels (de Ruiter *et al*. 2005), or, complementarily, representation of the distribution of community biomass over body sizes (Kerr and Dickie 2001). It will be important that we take account of these properties in forming our FooWI advice in order to develop pragmatic indicators at regional seas levels.

The link with emergent properties (i.e. the highest hierarchical levels of organization) allows the FooWI to address cumulative impacts, integrated dynamics and responses, detect indirect and unintended consequences, and evaluate trade-offs in the food web. These are often examined in the context of management strategy evaluation for evaluating and mitigating pressures.

Thus, here we define a FooWI as a quantifiable metric that elucidates important features or attributes (i.e., processes and properties) of food webs.

1.4 Expectations for the workshop

There were two main expectations for this workshop. First, we wanted two primary outcomes:

- A Short list of *Suggested FooWIs* for the MSFD Descriptor 4, but germane to other, related management contexts in Europe and Globally; and
- A *Defined Process* for selecting and developing such indicators.

This approach led to a two-part set of efforts: (i).identification and evaluation of those FooWIs that can be used, operationally, now, and (ii) identification of those FooWIs that hold promise in the near- to medium term future but that also require further development. One important corollary was, while in the process of broader FooWI evaluation, to also evaluate the three extant MSFD D4 indicators for their continued use or possible replacement. We also noted that the approach and indicator suite evaluated here will have global application. Thus, while maintaining an MSFD focus, we conducted the workshop cognizant of broader uses of FooWIs.

Second, we particularly wanted the workshop to avoid esoteric and highly theoretical debates; requests for monitoring or research to develop indicators without cognizance of existing FooWIs; advocating for non-FooWI and/or hyper-specific indicators; over-emphasizing select indicators without exploring the full suite of possible FooWIs; or using the workshop as a primary venue for proposal development for limited subsets of specific indicators. The emphasis was very much on pragmatic approaches to identify, use and continue to develop FooWIs.

2 Policy and Management Needs for Indicators

2.1 MSFD Context for FooWIs

The workshop was building on considerable work by EU Member States and Contracting Parties to Regional-Seas Conventions to develop coherent sets of FooWI for the MSFD. Earlier JRC/ICES work reported in Rogers *et al* (2010) identified three criteria of energy flows in the food web which were considered feasible to measure and apply at a regional scale: a) ratios of production at different trophic levels, b) the productivity (production per unit biomass) of key species or groups, and c) trophic relationships. At a structural level, monitoring the rate of change of functionally important species to highlight rapid in-creased or decreased abundance would also help to identify where future management action may be required.

To support their marine strategies, Member States had submitted sets of environmental targets and associated indicators to the EC in late 2012 (DG JRC (Palialexis *et al*. 2014) and DG ENV (COM/2014/097; SWD/2014/049). A recent evaluation of the submitted FooWI by the EU suggested that clearer guidance would allow Member States to choose FooWI more coherently within and across regions and lead to clearer state and pressure targets for GES for Descriptor 4, in accordance with the Commission's observation (2010/477/EU) that additional scientific and technical support is required for D4 targets and indicators.

The EC has therefore requested ICES to develop proposals on indicators for Descriptor 4 of MSFD (DG ENV request 1d). In this framework, ICES shall work towards recommendations for potentially useful indicators (to be considered for the revision of the Commission Decision) with a roadmap of how to get there. Needs for quantification and assessment of foodweb processes have become clear also in other European contexts. For example, HELCOM (2013) have established a set of core indicators within the CORESET project, and OSPAR Ecological Quality Objectives (OSPAR 2009), some of which relate to foodweb processes. Foodweb related indicators will also be among the products of marine surveys under the Data Collection Multi-Annual Plan (DC-MAP), and under the EU's Common Fisheries Policy (CFP) reductions of discards and adjustments of stock sizes to maximize yields are expected to affect the marine environment through foodweb processes of which management must be mindful.

2.2 Other Contexts for FooWIs

Examples of needs for FooWIs recognized by policy and management can also be found in North America and at an international level.

Food web indicators are central in Ecosystem Based Management activities of a diversity of U.S. government agencies and non-governmental organizations, and are used to support a number of management actions. For example, food web indicators are central to NOAA's Integrated Ecosystem Assessments (IEAs). Food web indicators are important to IEAs because they serve as proxies for many of the ecosystem services about which policy-makers and stakeholders are concerned. As such, food web indicators are one of the primary contact points between policy and science. A critical step in the IEA process is to generate food web indicators that are compelling to the public and decision-makers, but also capture the key food web states and processes that underlie critical ecosystem dynamics.

Canada's Oceans Act received Royal Assent in 1996, signalling a new direction for oceans management in Canada: sustainable; precautionary; ecosystem-based; integrated; and adaptable. The Oceans Act is the basis for an ecosystem approach to oceans management. Since 1996, DFO has developed new programs for oceans management and has been working to incorporate the principles of the Oceans Act into its traditional management sectors. A critical part of DFOs EAM is the development of ecological, foodweb indicators to assess the status of ecosystems. See Curran *et al*. 2012 for further details.

The IndiSeas project was established with the goal to conduct comparative analyses of ecosystem indicators to quantify the impact of fishing and to provide decision support for global policy drivers such as the 2020 targets of the Convention on Biological Diversity and for fisheries management in a context of climate variability and change. IndiSeas was established in 2005 as an international collaborative program under the auspices of the EUROCEANS European Network of Excellence and endorsed by IOC/UNESCO. Food web indicators are a critical component of this work and IndiSeas has published a series of papers assessing the status of ecosystem in a global, comparative framework (Shin *et al*. 2010, 2012 and references therein; www.indiseas.org). Currently IndiSeas is conducting analyses to evaluate the performance of a range of ecological indicators, including the MSFD large fish indicator and mean maximum length, using a multi-modelling, multi-ecosystem comparative approach.

There are many other instances where policy is dictating that ocean resource managers ask for scientists to provide and evaluate food web indicators. The instances above are meant to be exemplary, are by no means exhaustive, and signify the broader, potential applications of this work.

2.3 Key Discussion Points regarding FooWI Contexts

The explicit call for GES targets for food webs and supporting indicators by the MSFD is the expression of an emerging recognition of the need for working with FooWI when managing the marine environment. This trend reflects advances in science and management practices, by which the impacts of feeding interactions have moved into the centre of attention of management, policy, and the public.

However, the science of marine food webs continues to develop. As we continue to understand and predict the dynamics of food webs, we will need to simultaneously glean pertinent information to inform management. The most pragmatic approach towards a management of marine food webs will therefore often be that of carefully advancing as new information is developed.

3 Review of Indicator Selection Criteria

3.1 Background & the WKFooWI approach

Globally a set of best-practices is coalescing around indicator selection. A plethora of indicator selection criteria (which are distinct for indicator use criteria or for sets of criteria) have been developed that identify key facets of indicators. Largely building off the work of Rochet and colleagues (Rice and Rochet 2005, Rochet and Rice 2005, Piet *et al* 2008) a body of core criteria have been iteratively explored and mostly converged upon in the ICES context (e.g., WGECO 2008, 2010, WGBIODIV, WGFE, WGSAM). Other indicator efforts have also developed comparable selection criteria (FAO 1999, INDECO, IndiSeas, Methratta and Link, 2006; Link, 2005; Fulton, 2005). These are all based on a multicriteria decision analytic approach.

Indicator selection criteria will obviously depend on the use intended for the selected indicators. For example, it has often been recommended that indicators used for communication should be concrete, easy to understand, and the target audiences should be aware of the issue they are informing about. Other selection criteria might be more appropriate to indicators used in support of decision-making. Another important point is that indicators are generally not used in isolation – there is broad agreement that portfolios of indicators are required to address a given management problem. Therefore in the selection of criteria it is important to consider whether these criteria apply to individual indicators or to the suite of indicators, or both.

3.2 7 step framework (Rice and Rochet)

Criteria are just one ingredient in the process for selecting indicators. To organize the selection process, Rice and Rochet (2005) proposed a seven-step framework to be adapted to the specific settings and requirements of a given management problem:

1) Determine user needs
2) Develop a list of candidate indicators
3) Determine screening criteria
4) Score indicators against criteria
5) Summarize scoring results
6) Decide how many indicators you need
7) Final selection

The indicators discussed at WKFooWI are principally related to Descriptor 4 of the EU MSFD and other contexts of ecosystem-based management; therefore criteria related to practical management implementation were given specific emphasis. For management use, primary requirements are that indicators should be sensitive, have a basis in theory and be measurable. Broadly defined management objectives such as those in MSFD descriptor 4 need to be broken down into operational objectives for practical use in regional seas. Since food webs differ among regional seas, operational objectives might differ as well. The short list of evaluated, acceptable food web indicators provided does not imply that all should be developed and implemented in all regional seas – nor that other indicators should not be developed. Rather, Member States will need to select those appropriate to their regional seas, depending on the specific settings of the regional ecosystems and on data availability. Further, the phrasing of the MSFD descriptor 4 ("*All elements of the marine food webs […] occur at normal abundance* *and diversity and levels […]")* also suggests that food web indicators may include metrics related to the state of food web components (*e.g.*, species or species groups), in addition to the core attributes previously identified.

As for indicator scoring and score summaries, previous exercises have demonstrated that a misleading sense of precision can be gained from complex scoring systems (Rochet and Rice 2005, Piet *et al.* 2008). Robust outcomes would be expected from selection procedures relying on short lists of criteria – the most relevant to the management problem. However, this would only be the case if each criterion still addressed only single discrete aspects of indicator performance. Reducing a list of criteria by combining several, possibly closely related, aspects of indicator performance within a single criterion is not helpful. Should an indicator have variable levels of performance against these different aspects, this would present difficulties in assigning a particular score to the criterion, and tend to introduce variability of criterion scoring between individual expert assessors.

3.3 A methodology to assess OSPAR Common Indicators

In previous exercises, ICES have been asked to provide OSPAR with advice regarding the selection of a small coherent set of "common indicators", indicators to be used by all Member States sharing particular MSFD Regions or Subregions, from all possible indicators proposed by the individual Member States concerned.

To address this task WGECO and WGBIODIV recently developed a table of 16 criteria against which to assess the performance of each of the potential "common indicators". These criteria were initially synthesized from a set of criteria presented by Kershner *et al.*, (2011). Additional more recent papers dealing with indicator assessment criteria were also reviewed, but found to add no further criteria (WGBIODIV 2014). The resulting 16 criteria therefore take account of over 20 peer-reviewed publications.

WGBIODIV then developed an indicator assessment process based on these 16 criteria. Several of the indicators proposed by Member States were in fact pressure indicators and not state indicators, and some criteria were not applicable to pressure indicators. Criterion 1 therefore determined whether the indicator in question was a pressure indicator, and if so it was not subjected to further assessment. Criteria 2 to 15 constituted the actual assessment criteria and these were weighted in their importance; "core" criteria were given a weighting score of 3, "desirable" criteria a score of 2 and "informative" a score of 1. When assessing each indicator against each criterion, a "compliance" score of 1, 0.5 or 0 was given, and guidance was provided to indicate the type and level of compliance required to merit a particular score. An overall score for each indicator against each criterion was obtained by multiplying the "weighting" and "compliance" scores. Summing these overall scores across all 14 criteria (or 10 criteria for a pressure indicator) provided a "final assessment" score for each indicator.

Criterion "weighting" scores were agreed in consensus by WGBIODIV members prior to undertaking the assessment. WGBIODIV members then made their own "compliance" score assessments. Mean "final assessment" scores for each indicator could therefore be determined along with the range of values obtained. Where the range in "final assessment" scores was large, this provided an indication of higher than usual disagreement among expert group members concerning the performance of an indicator against a particular criterion. This could then be reviewed within the group to identify the issues involved. A simulation procedure, simulating 100,000 "virtual" indicators and assigning compliance scores at random, was used to provide an objective means of identifying indicators that might be considered to have a satisfactory level of performance. Thus in WGBIODIV's assessment, a "final assessment" benchmark score of 69% placed an indicator in the top 5% performance range.

Criterion 16 was a "tie-breaker", intended to guide selection between high-performing indicators, by forcing a choice between indicators that essentially fulfilled the same role.

WGECO (2013) followed this general protocol, evaluating some common and some novel indicators. The point being that WGECO used these best practice methods and obtained a similar set of consensus-based results.

3.4 Criteria selection

WGBIODIV undertook their assessment using 16 analytical criteria and accordingly the range of scores for each indicator against particular criteria tended to be narrow. To reduce the number of criteria used to assess potential food web indicators, WKFooWI discarded criteria in WGBIODIV's table that we felt were less relevant to food web indicators.

WKFooWI then cross-mapped these high-level considerations to more detailed criteria developed by work executed by ICES WGs (WGECO 2013). We settled upon very moderate revision to mostly extant and, increasingly within the ICES community, accepted definitions of indicator selection criteria.

The high level criteria applied incorporated the following concepts:

1) **Availability of data**. *Measurability*, robust quantifiable data covers range of spatial & temporal natural variability of suitable (historic) duration and resolution, availability of historic data or other reference points for benchmarking,

2) **Quality of underlying data.** Data that are *Sensitive* to the magnitude and direction of response to underlying attribute/pressure with high signal to noise ratio, and *Responsive* at an appropriate time-scale. A *tangible* indicator that is intuitive to understand.

3) **Conceptual,** *Theoretical basis*, with indicator behaviour (in response to pressure) that is understood to support management advice,

4) **Communication**, an indicator that is simple, credible, *unambiguous, comprehensible* and can be easily communicated

5) **Manageable**, an indicator that is relevant to management, with estimable targets and thresholds and which are *responsive, sensitive* and *cost-effective* to develop,

The salient points are that: there is consensus on the high level selection criteria; particular subcriteria definitions can always be argued over but were mostly agreed upon in principle; these criteria built upon extent work from ICES and related indicator WG efforts; and that this criteria-based selection process is coalescing into a best practice for indicators. (Table 3.1).

Table 3.1. Criteria used to evaluate food web indicators, based on those developed by WGBIO, and modified by WGECO.

CRITERIA	ISSUES	RATIONALE
Availability of underlying data (Measurable)	Existing and ongoing data	Indicators must be 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 (Sensitivity) (Responsive)	Indicators should be technically rigorous (tangible)	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 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 (Theoretical 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 (Concrete) (PubleAware)	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.

Criteria	Issues	Rationale
Management (Measureable) (Sensitivity) (Responsive)	Relevant to management	Indicator links directly to mandated management needs, and idealy to management response. The relationship between human activity and resulting pressure on the ecological component is clearly understood.
	[MSFD] management thresholds (targets) 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.
Indicator suites (Redundancy)-- *post criteria evaluation*	Indicator correlation & ambiguity (Size, Production, Canary, Aggregate, Energy Flow) [Aggregate = Guild, Functional Group, Structural partly, etc.; Network = Resilience, Structural partly, Functional partly etc.; Energy Flow = Functional partly]	Different indicators making up a suite of indicators should each reflect variation in different attributes of the ecosystem component and thus be complementary. Correlation between indicators should be ideally be avoided, and multiple aspects of the food web should be examined.
	Useful for other MSFD Descriptors	The indicator obviously relates to foodwebs, but may be useful to adress issues linked to or be informed by other MSFD descriptors too.
	Functional Group coverage (PP, ZP, Benthos, Forage Fish, Fish, Charismatic Megafauna)	Functional Group coverage (PhytoPlankton, ZooPlankton, Benthos, Cephalopods, Forage Fish, Fish, Birds, Mammals, Reptiles). Integrated is for indicators that cover processes or attributes across the whole food web.
	FW Attributes Coverage	Attributes include: structure (that is, related to the components of the food web and the distribution of matter among them); functioning (that is, related to the flows through and/or between these components); and resilience (that is, properties that contribute to the ability of the ecosystem to recover after a significant perturbation).

3.5 Further considerations relevant to the selection of a portfolio of food web indicators

In addition to the specific criteria for each FooWI, we also noted a broader set of features to consider when evaluating the full suite of FooWIs (Table 3.1). These are variously termed attributes, categories, indicator suite criteria, or similar phraseology depending upon the context. The point of our using these was to establish them so that key Food Web attributes were not omitted by any unintended potential biases by expertise and participation at the workshop.

These additional considerations include:

- Relation to other MSFD Descriptors

- The primary food web attribute (structural, functional, resilience);
- Indicator class (energy flow, network, canary, diversity, size, aggregate);
- Food Web Functional group:
- PhytoPlankton
- ZooPlankton
- Benthos
- Cephalopods
- Fish
- Birds
- Mammals
- Reptiles
- Integrated (that cover processes or attributes across the whole food web.)

3.6 Key Discussion Points regarding Indicator Selection Protocols & Criteria

- WKFooWI built on prior ICES work related to indicators, and particularly FooWIs selection criteria
- WKFooWI used internationally recognized best practices to identify and utilize indicator selection criteria
- Ensuring the selection criteria follow generally accepted protocols and delineations is useful, but any given exercise or context warrants the need for necessary modifications as is appropriate. Fortunately, those were relatively minor in this instance.

4 Indicator Responses and Thresholds

4.1 The need for Indicator Responses and Thresholds

There is a clear need to establish indicator responses and thresholds. A general overview of different processes for examining thresholds in indicators, and their potential use for informing ecosystem-based management reference points was presented. First introduced was a quantitative, transferable method for identifying utility thresholds. A utility threshold is the level of human-induced pressure at which small changes produce substantial improvements toward the EBM goal of protecting an ecosystem's structural and functional attributes. The analytical approach is based on the detection of nonlinearities in relationships between ecosystem attributes and pressures, and the method was illustrated with a case study of (1) fishing and (2) nearshore habitat pressure for British Columbia, Canada. Secondly, a structured approach for choosing among three classes of reference points was noted, including: (1) functional relationships that establish the ocean state that can be produced and sustained under different environmental conditions, (2) time-series approaches that compare current to previous capacities to obtain a particular ocean state in a specific location, and (3) spatial reference points that compare current capacities to achieve a desired ocean state across regional (or, if necessary, global) scales.

Finally, Levin provided an overview of a method in which indicator-pressure relationships were examined and used to inform target setting in Puget Sound. In this case, all indicators where examined as a portfolio, and targets for individual indicators were developed through stakeholder process that focused on stakeholder's desire for specific ecosystem states.

These examples demonstrated not only the need for thresholds, but also how they have been obtained elsewhere.

4.2 Methods and Examples for Estimating Indicator Responses and Thresholds

Establishing decision criteria that trigger management actions for EBFM 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 (Martin *et al*., 2009; Samhouri *et al*., 2010). Samhouri *et al*. (2010) used simulation models that examine ecosystem response to fishing pressure and nearshore habitat exploitation. In both scenarios, increased pressure resulted in a shift towards negative ecosystem status and decision criteria were suggested for management action. Similarly, empirical approaches (Link *et al*., 2002; Coll *et al*., 2010; Link *et al*., 2010; Blanchard *et al*., 2010) have also been used to examine pressure – response relationships and determine indicator levels where pressure variables result in ecosystem change. However, these studies only provide general levels where pressure variables result in ecosystem change.

Using indicators to inform management to the point of delineating control rules or decision points requires an understanding of potential ecological thresholds, which occur when a small change in a pressure results in a large response in ecosystem state or function (Groffman *et al*. 2006, Martin *et al*. 2009). Mathematically, univariate thresholds occur when the second derivative of a function crosses zero, denoting a change in the function (e.g., from concave-up to concave-down) and can be calculated from known functional forms such as piecewise regression models (Chaudhuri and Marron 1999, Toms and Lesperance 2003, Sonderegger *et al*. 2008, Samhouri *et al*. 2010), or estimated from generalized additive models using finite differences (Fewster *et al*. 2000, Large *et al*. 2013). Ecological thresholds have been theoretically and empirically evaluated in response to fishing and environmental pressure (Link 2005, Samhouri *et al*., 2010, Fay *et al*., 2013, Large *et al*., 2013). These univariate relationships are useful for establishing decision criteria (Fay *et al*. 2013, Large *et al*. 2013), however, they do not fully account for multiple pressures that likely interact and occur concurrently.

Univariate thresholds have been extended into bivariate space by translating indicator response into a surface dependent on multiple pressures (i.e., fishing and environmental pressure; Frederickson *et al*., 2004; Scott *et al*., 2006; Large *et al*., *In Review*). Critical points, or bivariate thresholds, occur when the slope (i.e., partial first derivative) of both pressure variables is equal to zero, and with the second partial derivative test, local maximum, local minimum, and saddle points can be identified. Therefore, critical points in bivariate response-pressure relationships describe regions where both pressures result in a large response (i.e., change in magnitude or direction) in ecosystem state or function. Therefore, we identify levels of multiple pressure variables (i.e., fishing and environmental pressure) that result in a significant response of indicator value. Understanding how multiple pressure variables concurrently influence ecosystem status provides much more salient management advice.

4.3 Resilience and Indicators

Resilience is a key aspect of ecosystem behaviour and environmental status. A resilient system reacts only weakly to pressure, until resilience is overcome and the system then changes rapidly to a different state or regime. Such transition is thus the result of an accumulation of the disturbing effects of pressure. Additionally, ecosystems may exhibit legacy effects of earlier pressures. Whereas an indicator (I1) that points to a disturbed component may show an immediate response to a change in pressure, a more holistic indicator (I2) of ecosystem structure or functioning may lag the pressure change and show a significant response only as the system changes. Ideally, ecological understanding will allow present changes in I1 to predict future changes in I2, but this is not currently possible in all cases. Indicators of type I2 are needed for evaluation of GES, whereas those of type I1 are more directly useful for guiding management action.

So while it was recognized that structure and functioning of food webs were the major attributes for which indicators were required, the resilience of food webs was a component which in this exercise was treated as an additional attribute.

4.4 Key Discussion Points regarding Indicator Responses and Thresholds

- Thresholds are needed for indicators if they are to directly inform management decisions
- There are many extant methods to determining thresholds of FooWIs
- These are not commonly practiced, but represent a key need for future indicator development

5 Indicators presented to WKFOOWI

5.1 Presentation of food web indicators

Members of the workshop were asked to prepare short presentations of indicators of the structure and functioning of food webs: over 60 candidate indicators were described. Each presenter was asked to address a common set of questions for each indicator to enable subsequent evaluation. Presentations covered all marine functional groups and all attributes of food webs that were considered necessary for a comprehensive evaluation. Sufficient information was provided to allow the indicators presented to be scored against a set of criteria, and later prioritized to support the development of a Roadmap.

On further review of the indicators presented, it was evident that several were duplicates and some were inappropriate. A list of 40 candidate FooWIs is given in Table 5.1, grouped into the three main food web attributes, Functional Indicators linked to Energy Flow, Functional Indicators linked to Ecosystem Resilience and Structural Indicators linked to diversity and 'canary' species.

Table 5.1a Assessment of selected food web indicators, grouped by attribute, against the criteria listed in Table 3.1. ranking applied was 0 = no, 1 = somewhat, 2 = very much, as following the protocol devised by WGBIODIV. Table comprises of four panels with the indicators divided into 2 groups, with scorings provided in first two panels and the synthesis given in the second two panels.

Scoring of candidate indicators (first grouping)

	Selection Criteria												
	Avalability of underlying data (Measurable)			Quality of underlying data (Sensitive) (Responsive)			Conceptual (Theoretical Basis)			Communication (Concrete) (Public Aware)	Management (Measureable) (Sensitive) (Responsive)		
Name of candidate indicator	Existing and ongoing data	Relevant spatial coverage	Relevant temporal coverage	Indicators should be technically rigorous (tangible)	Reflects changes in ecosystem component that are caused by variation in any specified manageable pressures	Magnitude, direction and variance of indicator estimable	Scientific credibility	Associated with Key processes	UnAmbiguous	Comprehensible	Relevant to management	manageme nt thresholds (targets) estimable	Cost-effectivene
Seabird breeding success	2	2	2	1	1	1	2	2	2	2	1	2	2
Productivity (production per unit biomass) of key predators.	2	2	2	1	1	1	1	2	1	1	1	1	2
Mean weight at age of predatory fish species from data	2	1	1	2	1	2	2	2	1	2	1	2	2
Total Mortality (Production:Biomass ratio)	2	1	1	2	2	1	1	2	1	1	2	2	1
Primary production required to support fisheries	1	2	1	1	1	1	2	2	2	0	2	1	2
Productive pelagic habitat index (chlorophyll fronts)	2	2	2	2	1	1	1	2	1	1	1	0	2
Ecosystem Exploitation (fisheries)	2	2	1	1	2	0	2	0	0	1	2	2	1
Community Condition	1	1	1	2	1	2	1	1	1	2	1	1	1
Mean trophic level of catch	1	2	1	1	2	1	2	0	0	1	2	1	1
Marine Trophic Index of the community (MTI)	1	2	1	1	1	1	2	2	0	1	1	1	1
mean trophic level of the community	1	2	1	1	1	1	2	2	0	1	1	1	1
Disturbance index	1	2	1	1	1	1	2	2	0	1	1	0	1
Loss in secondary production index (L index)	1	2	1	1	1	1	2	2	0	0	1	1	1
Cumulative distribution of biomass assessment	1	2	1	1	1	1	2	2	0	0	1	1	1
Trophic Balance Index (fishing pattern)	1	2	1	1	1	0	2	1	0	0	1	2	1
Mean transfer efficiency for a given TL or size.	1	1	1	0	1	1	2	2	0	0	0	0	1
Finn Cycling Index	1	1	1	0	1	0	2	2	0	0	0	0	1

Table 5.1b Assessment of selected food web indicators, grouped by attribute, against the criteria listed in Table 3.1. ranking applied was 0 = no, 1 = somewhat, 2 = very much, as following the protocol devised by WGBIODIV. Table comprises of four panels with the indicators divided into 2 groups, with scorings provided in first two panels and the synthesis given in the second two panels.

Scoring of candidate indicators (second grouping)

	Avalability of underlying data (Measurable)			Quality of underlying data (Sensitive) (Responsive)			Conceptual (Theoretical Basis)			Communication (Concrete) (Public Aware)	Management (Measureable) (Sensitive) (Responsive)		
Name of candidate indicator	Existing and ongoing data	Relevant spatial coverage	Relevant temporal coverage	Indicators should be technically rigorous (tangible)	Reflects changes in ecosystem component that are caused by variation in any specified manageable pressures	Magnitude, direction and variance of indicator estimable	Scientific credibility	Associated with Key processes	UnAmbiguous	Comprehensible	Relevant to management	management thresholds (targets) estimable	Cost-effectiveness
Mean trophic links per species	1	1	1	2	0	0	2	2	0	1	1	0	1
Ecological Network Analysis derived indicators (overall mean transfer E	2	1	1	0	1	0	2	2	0	1	1	0	1
Gini-Simpson dietary diversity index	1	1	1	2	0	0	2	2	0	1	1	0	0
Herbivory : detritivory ratio	1	1	1	0	1	0	1	2	1	1	0	0	1
Ecological network indices of ecosystem status and change (Ulanowicz)	2	1	1	0	1	0	2	2	0	0	0	0	1
System Omnivory Index	1	1	1	0	1	0	1	1	0	0	0	0	1
Guild surplus production models	2	2	2	2	2	2	2	2	2	1	2	2	2
Total biomass of small fish	2	2	2	2	1	2	2	2	1	2	1	2	2
Proportion of Predatory Fish	2	2	2	1	1	1	2	2	1	2	2	2	2
Pelagic to demersal ratio	2	2	2	2	1	2	1	2	1	2	1	1	2
Biomass of trophic guilds	2	1	1	1	1	1	2	2	1	2	2	2	2
Lifeform-based indicator for the pelagic habitat	2	2	2	2	1	2	2	1	1	1	1	1	2
Region-specific indicators of abundance & spatial distribution	2	2	2	1	0	2	2	1	1	1	2	2	1
fish biomass/benthos biomass from models	2	1	1	1	1	1	1	2	1	2	1	1	2
Zooplankton spatial distribution and total biomass	2	1	1	2	1	1	1	2	0	2	1	2	1
Scavenger biomass	1	1	1	2	1	2	2	2	1	1	2	1	2
Geometric mean abundance of seabirds	2	2	2	1	1	1	2	2	1	1	1	1	2
Gini-Simpson diversity index (species dominance) of large & small fish	2	2	2	1	0	1	1	1	0	0	1	1	2
Species Richness Index	2	2	2	1	0	1	1	1	0	2	1	0	1
Large Fish Indicator LFI)	2	2	2	2	2	2	2	2	1	2	2	2	2
Mean length of surveyed community	2	2	2	2	2	2	2	2	0	2	1	1	2
Size spectra slope	2	2	2	2	1	1	2	2	0	1	1	1	2
Zooplankton Mean Size - Total community biomass index	2	1	1	2	1	1	1	2	0	2	1	2	1

Table 5.1c Synthesis of scoring of selected food web indicators, grouped by attribute. (first grouping)

	Indicator suites (Redundancy)--*post criteria evaluation*						
Name of candidate indicator	Indicator correlation with attribute	Useful for other MSFD Descriptors (Note which Descriptor)	Current Functional Group	Food Web Attributes	max score 13 x 2	26	Future Functional Group
Seabird breeding success	Energy Flow; Canary	*D1*	bird	Functioning	22	85%	bird
Productivity (production per unit biomass) of key predators.	Energy Flow; Canary		mammals, birds, reptiles, fish	Functioning	18	69%	mammals, birds, reptiles, fish
Mean weight at age of predatory fish species from data	Energy Flow; Aggregate	D3	fish	Functioning	21	81%	fish
Total Mortality (Production:Biomass ratio)	Energy Flow	D3	fish, ceph, benthos, mammal, bird, reptile	Functioning	19	73%	fish, ceph, benthos, mammal, bird, reptile, Forage
Primary production required to support fisheries	Production	D3, *D1*	Integrated, fish, benthos, ceph	Functioning	18	69%	Integrated, fish, benthos, ceph, mammals
Productive pelagic habitat index (chlorophyll fronts)	Production	D5, D3, D1	PP, fish, mammals	Functioning	18	69%	PP, fish, mammals, LTL, birds
Ecosystem Exploitation (fisheries)	Energy Flow	D3	fish, ceph, benthos, mammal, bird, reptile	Functioning	16	62%	fish, ceph, benthos, mammal, bird, reptile, Forage
Community Condition	Energy Flow; Aggregate	D3	fish	Functioning	16	62%	fish, benthos
Mean trophic level of catch	Energy Flow; Aggregate	D3	fish, benthos, ceph	Functioning	15	58%	fish, benthos, ceph
Marine Trophic Index of the community (MTI)	Energy Flow; Aggregate		fish, Integrated	Functioning	15	58%	Integrated
mean trophic level of the community	Energy Flow; Aggregate		Integrated	Functioning	15	58%	Integrated
Disturbance index	Energy Flow	D3	fish, ceph, benthos, mammal, bird, reptile	Functioning	14	54%	fish, ceph, benthos, mammal, bird, reptile, Forage
Loss in secondary production index (L index)	Energy Flow	D3	fish, Integrated	Functioning	14	54%	Integrated
Cumulative distribution of biomass assessment	Energy Flow		Integrated	Functioning	14	54%	Integrated
Trophic Balance Index (fishing pattern)	Energy Flow	D3	fish, ceph, benthos, mammal, bird, reptile, Forage	Functioning	13	50%	fish, ceph, benthos, mammal, bird, reptile, Forage
Mean transfer efficiency for a given TL or size.	Energy Flow		Integrated	Functioning	10	38%	Integrated
Finn Cycling Index	Network; Energy Flow		Integrated	Functioning	9	35%	Integrated

Table 5.1d Synthesis of scoring of selected food web indicators, grouped by attribute. (second grouping)

Name of candidate indicator	Indicator correlation with attribute	Useful for other MSFD Descriptors (Note which Descriptor)	Current Functional Group	Food Web Attributes	max score 13 x 2	26	Future Functional Group
	Indicator suites (Redundancy)–*post criteria evaluation*						
Mean trophic links per species	Network	*D1*	fish	Resilience	12	46%	fish, integrated
Ecological Network Analysis derived indicators (overall mean tr	Network; Energy Flow		Integrated	Resilience ; Functioning	12	46%	Integrated
Gini-Simpson dietary diversity index	Network		fish,	Functioning; Resilience	11	42%	fish, ZP, Benthos, Forage, Charismatic
Herbivory : detritivory ratio	Network; Energy Flow		Integrated	Functioning; Resilience	10	38%	Integrated
Ecological network indices of ecosystem status and change (Ula	Network; Energy Flow		Integrated	Resilience ; Functioning	10	38%	Integrated
System Omnivory Index	Network; Energy Flow		Integrated	Functioning; Resilience	7	27%	Integrated
Guild surplus production models	Production; Aggregate	D3	fish, benthos	Structure	25	96%	fish, ZP, Benthos, Forage, Charismatic
Total biomass of small fish	Aggregate	D3	fish	Structure	23	88%	fish
Proportion of Predatory Fish	Aggregate	D1, D3	fish	Structure	22	85%	fish
Pelagic to demersal ratio	Aggregate	D3, D5	fish	Structure	21	81%	fish
Biomass of trophic guilds	Aggregate	D3, D1	fish	Structure	20	77%	fish, all
Lifeform-based indicator for the pelagic habitat	Aggregate	D5, *D6*, D1	PP	Structure; Functioning	20	77%	pelagic habitat (LTL)
Region-specific indicators of abundance & spatial distribution	Aggregate	D1, D3	fish	Structure	19	73%	fish, all
fish biomass/benthos biomass from models	Aggregate	D6, D3, D1	fish, Benthos	Structure	17	65%	fish, Benthos
Zooplankton spatial distribution and total biomass	Aggregate	D1, D5	ZP	Structure	17	65%	pelagic habitats
Scavenger biomass	Canary	D6, D1	Benthos, fish	Structure	19	73%	Benthos, fish
Geometric mean abundance of seabirds	Canary	D1	birds	Structure	19	73%	birds, all verts or UTL
Gini-Simpson diversity index (species dominance) of large & sm	Diversity	D1	fish	Structure	14	54%	Integrated and subsets
Species Richness Index	Diversity	D1	Integrated	Structure	14	54%	Integrated
Large Fish Indicator LFI)	Size	D3, D3	fish	Structure	25	96%	fish
Mean length of surveyed community	Size	D3, *D1*	fish	Structure	22	85%	UTL, LTL, Benthos
Size spectra slope	Size	D3, D1, D6	fish, intergrated	Structure	19	73%	Integrated and subsets
Zooplankton Mean Size - Total community biomass index	Size; Aggregate	D1, D5	ZP	Structure	17	65%	ZP

5.2 Functional Indicators linked to Energy Flow

5.2.1 Seabird breeding success

Many species of seabirds feed on lower trophic level forage species such as krill, squid, and pelagic fish. Seabirds summarize changes in these forage species communities that are often linked to patterns of exploitation (Cury and Christensen, 2005, Cury *et al*., 2011). Seabird breeding success has been consistently monitored across many ecosystems and provides robust estimates of both forage fish abundance and success of charismatic species (Cury *et al*. 2011, Wooler *et al*., 1992). Seabird breeding success can be a useful indicator, however, it may overlap with other measures of forage fish success.

5.2.2 Productivity (production per unit biomass) of key predators

Metrics characterizing productivity of predators at high trophic levels have been identified by Rogers *et al*., (2010) as an important class of foodweb indicators. They argued that "[t]he abundance of species in the food web will generally be determined by the abundance of suitable prey taxa on which they can feed. Some species, or groups of species, may play a significant part in food web dynamics and so their population status will effectively summarize the main predator-prey processes in the part of the food web that they inhabit." Food quantity or quality is known to affect survival and reproduction of many marine species including birds (Wanless *et al*.; 2005), mammals (Soto *et al*., 2006) and fish (Litzow *et al*., 2006). It has been argued (Boyd *et al* 2006, Rogers *et al*., 2010, Cury *et al*., 2011) that required prey abundance to quantitatively and qualitatively sustain viable populations of predators constitutes a threshold value which can serve as a reference point for productivity based indicators. "Productivity (production per unit biomass) of key species or trophic groups" was listed among the Criteria for GES by the EC (EU, 2010). Among others, it has been implemented in form of the HELCOM (2013) core indicators "Pregnancy rates of marine mammals", "White-tailed eagle productivity", "Abundance of sea trout spawners and parr", and "Abundance of salmon spawners and smolt".

5.2.3 Mean weight at age of predatory fish species from data

Fish weight and condition metrics provide information on state (e.g., food limitation) in an ecosystem. The indicator proposed by Shephard *et al*., (2014) describes the average "weight anomaly" for the pelagic fish community in a given year, which is the deviation around an observed long-term mean. The youngest and oldest age-groups of each stock are excluded to avoid sampling bias (see Table 1 for selected age ranges). Values are then averaged over all ages for each stock to obtain a mean annual anomaly for that stock. Stock anomalies are then averaged by year to obtain a regional mean weight anomaly for the whole pelagic or predatory fish communities, respectively, where indicator values should fluctuate around zero in the long term. The comparison between species and stocks can give additional information on whether food becomes limiting in general or whether just some species or trophic guilds are impacted.

Changes in this indicator can be caused by changes in food availability as well as an increase or decrease in predator populations. The demand for food can be also influenced by temperature. Therefore, the indicator should be only interpreted in conjunction with additional information (e.g. biomass of forage fish, benthos, sea temperature, predator abundance, etc.). The indicator will respond predominantly to non-anthropogenic impacts, and to a lesser degree to indirect anthropogenic impacts through food limitation.

5.2.4 Total Mortality (Production:Biomass ratio)

Total mortality has a large effect on both year-to-year survival, long-term reference points such as FMSY and resilience. If mean weight of a species in the stock and catch remain constant over time, this indicator is conceptually equivalent to production/biomass. Further, the inverse of total mortality is a direct indicator of longevity, an indicator which is often more readily communicated outside the scientific community. It responds to management through direct fishing mortality and the abundance of predatory fish (WGSAM; ICES 2012, 2013).

5.2.5 Primary Production Required to support fisheries

Solar radiation is fixed by phytoplankton and provides energy for marine ecosystems. Subsequently, energy is transferred through food webs by predation and lost through metabolic processes. Ecosystem production results from the conversion of organic matter at each trophic level and depends on ecological features such as the number of feeding links, the efficiency of energy transfer from one trophic level to the next, and temperature (Chassot *et al*., 2010). Production available to fisheries depends upon fishing mortality and targeted trophic levels in the food web. Fisheries focusing only on lower trophic levels may be energetically more efficient than those focused on top predators (Pauly & Christensen 1995; Gascuel & Pauly 2009).

Primary Production Required (*PPR*) is the primary production and detritus flows from TL 1 that are required to sustain fisheries (expressed as t/km^2/year). This allows the evaluation and comparison of fishing activities across ecosystems. The *PPR* is obtained by calculating the flows backwards, expressed in primary production and detritus equivalents, for all pathways from the caught species down to the primary producers and detritus. The *PPR* increases with fishing intensity. *PPR* has been analysed also in reference to PP, to reflect a percentage of PP used to sustain catches.

5.2.6 Productive pelagic habitat index (chlorophyll fronts)

Productive fronts (chlorophyll-a fronts) are key features in marine ecosystems since they last long enough to sustain zooplankton production and are considered one of the main vectors of ocean's productivity along the food chain (Le Fèvre 1986, Olson *et al*., 1994, Kirby *et al*., 2000, Polovina *et al*., 2001, Belkin *et al*., 2009, Druon *et al*., 2011, 2012). Pelagic habitats can be considered to indicate the general ecosystem productivity or related to a specific species.

The frequency of chlorophyll-a fronts within an intermediate range of chlorophyll-a content identifies the productive features that attract top-predators, i.e. areas of efficient energy transfer between trophic levels outside of low and high chlorophyll levels (from about 0.1 to 3.0 mg.m^{-3}). Indeed, high chlorophyll levels potentially correspond to potentially eutrophic areas where the food chain is disrupted and primary production is not available to upper trophic levels. Eutrophication and hydrological and atmospheric forcing are captured by this indicator, but it provides in particular the variability of ecosystem productivity available to high tropic levels independently of fishing pressure.

The indicator of pelagic productivity results from the demonstrated links between top-predators and chlorophyll-a fronts such as for fast-moving predators (Atlantic bluefin tuna, Druon 2010, Druon *et al*., 2011, and fin whale, Druon *et al*., 2012) and demersal nurseries (hake, Druon *et al*., in prep.) in the Mediterranean Sea. The generic index of productive pelagic habitats yet requires a formal validation at European scale (https://fishreg.jrc.ec.europa.eu/fish-habitat).

5.2.7 Ecosystem exploitation (fisheries)

This estimates the level of exploitation, integrated over all trophic levels, as the total yield divided by total production for all exploited species. Required data: Yield, biomass and production to biomass ratio for each species in the yield.

5.2.8 Community Condition

Community condition is a measure of the overall condition (average weight at length) at the functional group level, and the overall community condition. Condition reflects food availability: fish are heavier per unit length when food abundance is plentiful and/or competition for food is low, and lighter when food abundance is low and/competition for food is high. It is a reflection of energy flow, food availability and resilience.

Area and functional group specific mean community condition "K" was calculated as the abundance (a) weighted K from all individual species (i) within the functional group with length (l) and weight (w) data.

5.2.9 Mean trophic level of the catch

Mean trophic level of the catch is one of a suite of trophic level indicators that is based on the average biomass weighted trophic level across all species. Initial work considered the mean trophic level of the catch, based on fishery-dependent catch or landing statistics (Pauly *et al*., 1998). It describes the average trophic level at which species are removed by the fisheries. As more valuable upper-trophic level fish stocks are depleted, fishers may target lower-value, lower- trophic level fish stocks (Pauly *et al* 1998). Recent work suggests that this indicator is a better indicator of fishing pattern and pressure than an indicator of ecosystem state (Shannon *et al*., MEPS, *in press*).

5.2.10 Marine trophic index of the community (MTI)

The marine trophic index (MTI) (Pauly and Watson 2005) is another trophic level indicator, calculated with a cut-off point of trophic level greater than 3.25. Originally calculated from fisheries landings data, here it is presented as the MTI of the community, based on scientific survey data, and is considered an indicator of food web functioning (Shannon *et al* in press). It has most commonly been applied to fish (and cephalopods), but could be extended to a wider range of taxa. The marine trophic index of the community, like the mean trophic level of the community (see below), provides a measure of ecosystem integrity and resilience. Declining trophic levels may result in shorter food chains, which may leave ecosystems less able to cope with natural or human-induced change.

5.2.11 Mean trophic level of the community

Average trophic level (TL) obtained from fishery-independent surveys is a commonly used metric that can be used to measure status and trends of ecosystem structure and functioning (Shin *et al.,* 2010). Average TL of the community is expected to decrease in response to fishing, as fisheries tend to target species at upper trophic levels (Pauly *et al.,* 1998). Additionally, fishing can also change the structure of marine food webs by reducing the mean TL and might also influence ecosystem functioning by shortening the length of food chains and releasing predation on lower trophic level organisms (Shin *et al.,* 2010).

5.2.12 Disturbance index

The disturbance index (DI) measures the change in trophic (or size) structure of the ecosystem and is calculated as the sum, across all TLs ≥2 (or size classes), of the absolute difference in the relative biomass (B_{TL}/B_{Total}) within each TL for each year, relative to a reference period (Bundy *et al.*, 2005). The reference period can represent a preferred state of the ecosystem, an ideal state, a theoretical state estimated from an ecosystem model or the beginning to the time period for which there is data. The DI has been shown to respond directly to fishing pressure, but may also be affected by other pressures such as environmental change.

The DI was originally proposed as one of 4 indicators comprising a 4D ecosystem exploitation index (Bundy *et al.*, 2005).

5.2.13 Loss in secondary production index (L index)

The decrease in secondary production was proposed as a proxy for quantifying ecosystem effects of fishing on the basis of a theoretical development and application to a large set of data (Libralato *et al.*, 2008). L index is calculated by integrating the primary production required to sustain the catches (PPR; Pauly and Christensen, 1995) relative to the primary production (PP) in the ecosystem, the transfer efficiencies (TE, i.e., the efficiency in the transfer of energy from a trophic level to another; Lindeman, 1942) and the trophic level of the catches (TLc; Pauly *et al.*, 1998). Theoretically, these inputs can be combined to measure the loss in secondary production due to fishing (L index) and to evaluate ecosystem effects of all fished species (Libralato *et al.*, 2008).

The application of the L index to a set of well-studied models allowed a probability of being sustainably fished (Psust) to be associated with each L index value, and, by fixing desired sustainability levels (e.g., 75% and 95%) it provide the basis for back-estimating the associated Ecosystem-based Maximum Sustainable Catches (EMSC) (Libralato *et al.*, 2008).

Thus L index is formally defined as an index of ecosystem overfishing and allows application of the index using both landings data and ecosystem models. L index can give rough estimates of overfishing status and management advice measures allowing definition of a region of viable solutions (sensu Cury *et al.*, 2005). L index quantification can be adapted to specific spatial scales (regional spatial assessment) and to large pelagic areas exploiting data from satellite for estimating PP, catches and available data on diets (for TL estimates).

5.2.14 Cumulative distribution of biomass assessment

Accumulation of biomass has been documented for many marine food webs, with the intermediate TLs exhibiting the largest increase in the system cumulative biomass (Gascuel *et al.*, 2005, Link *et al.*, 2009). Changes in this accumulation may reflect shifts in the ecosystem structure and function. According to these observations, from a theoretical point of view, a perturbed ecosystem should lower the stored, cumulative biomass and “stretch out” across TLs. To describe and quantify these curve shape modifications, the biomass distribution across TLs is fitted to a logistic non-linear regression model in order to estimate the main curve parameters: steepness (that is the slope of the tangent passing through the inflection point), inflection TL (that is the projection of the inflection point on the x-axis), inflection CumB (that is the projection of the inflection point on the y-axis), and the basal biomass (that is the y-axis intercept of the fitted curve). Applications, carried out by using both surveys and landings data, showed that the method is robust to possible 'sampling errors' (in terms of TL assignment), sensitive to both environmental and anthropogenic drivers, and when applied to fishery dependent data, responsive (Pranovi *et al*., 2012; 2014).

5.2.15 Trophic balance index (Fishing pattern)

This index measures the evenness (pattern) of exploitation across TLs by comparing their exploitation rates, which are estimated as the sum of yield (Y) divided by the sum of production (P) at each TL. The evenness of exploitation is then given by the coefficient of variation of all Y/P. Required data: Yield, biomass and P/B for each species in the yield.

5.2.16 Mean transfer efficiency for a given TL or size

The transfer Efficiency (TE_{TL}) is defined as the fraction of production that is passed from one integer trophic level to the next (Lindeman, 1942; Pauly and Christensen, 1995). It is thus quantifiable as the ratio between the production of the trophic level (TL) and the production at the precedent trophic level (TL-1). Several studies have estimated the pattern of TE by different trophic level after Lindeman's work (Lindeman 1942; Burns, 1989; Strayer, 1991). It has been used as a diagnostic indicator in some cases (e.g., Libralato *et al*., 2004) but in most instances it has been used as a mean ecosystem average (the overall mean transfer efficiency).

5.2.17 Finn Cycling Index

The Finn's cycling index (FCI, Finn 1976) is the proportion of the total sum of flows in the food web that is recycled in the system. It is measured as the proportion of the total flow that is flowing within circular pathways. Recycling is considered to be an indicator of an ecosystem's ability to maintain its structure and integrity through positive feedback and is used as an indicator of stress and maturity (Ulanowicz, 1986; Christensen 1995; Monaco and Ulanowicz 1997; Vasconcellos *et al.*,\ 1997). FCI is an indicator of the recovery time of an ecosystem through development of routes to conserve nutrients. A high FCI would mean the system would recover faster from a perturbation, whereas a system would be expected to take longer to recover (lower FCI) when it is in a more degraded state.

5.3 Functional Indicators linked to ecosystem resilience

5.3.1 Mean trophic links per species

The mean trophic links per species reflects how connected a food web is and, potentially, how stable a food web may be (Link 2002, Link 2005, Methratta and Link 2006). Changes to this indicator reflect notable differences in the structure and dynamics of a food web. As an understanding of temporal and spatial characteristics of marine trophic interactions it may not be entirely complete. This index should be used only as a tool to invoke further precautionary action (Link 2005).

5.3.2 Ecological Network Analysis derived indicators (overall mean Transfer Efficiency)

The mean transfer efficiency (TE_m) for the food web is calculated as the geometric mean of transfer efficiencies for each of the integer trophic levels II to IV from models (Christensen *et al*., 2008). There have been attempts to estimate average TE also on the basis of catches over trophic levels on the assumption that fisheries were in balance for some periods (Pauly and Palomares, 2005) – which would provide a fishing pressure indicator. Average transfer efficiency by ecosystem type based on model outputs have shown some variability across ecosystem types (Libralato *et al*., 2008) and other pressure factors as it has been shown in Heymans *et al*., (2012). It has been proposed as a descriptor of ecosystem health in lakes (Xu & Mage 2001, Hecky 2006).

5.3.3 Gini-Simpson dietary diversity index

The Gini-Simpson dietary diversity index is defined as the average, over a representative sample of consumer species, of the Gini-Simpson diversity of the contributions of resource species to consumer diets, by volume or biomass (Rossberg *et al* 2011, ICES, [WGSAM] 2012, Rossberg 2013). It can be determined from stomach-content data. The metric attains values between 0 and 1, with 0 implying no diversity and 1 high diverse.

$$1-\frac{\sum_{ij}[\![(p]\!]_{ij})^2}{\sum_{ij}p_{ij}} \quad p_{ij}\ i\ j$$

The indicator may be applied to any component of the ecosystem for which diet data are available, but has so far been computed only for fish (Rossberg *et al* 2011). A target for the metric near 0.5 has been proposed (Rossberg *et al* 2011, Rossberg 2013), based on theory and observation data. The indicator may respond to pressures (e.g. Rossberg *et al.*, 2011).

5.3.4 Herbivory : detritivory ratio

This indicator, proposed by Ulanowicz (1992), is the ratio of the values of the detritivory flow (from detritus to level II) divided by the value for the herbivory flow (from primary producers to level II). It is sometimes presented as H/D (then abbreviated HDR). This indicator was inspired by Lindeman (1942) when he referred to the role of saprophageous organisms and heterotrophic bacteria. This ratio has already been tested as a candidate for defining functional indicators of the food web, but results seem to be case sensitive. For example, Ulanowicz (1992) observed a lower Detritivory / Herbivory ratio in disturbed situations whereas Dame & Christian (2007) observed exactly the opposite trend. Then the disturbed situation showed a shift to a more detritus-based food web.

5.3.5 Ecological Network indices of ecosystem status and change (Ulankowicz)

The Redundancy (R) (Monaco and Ulankowicz 1997) indicates the system's energy in reserve and is an indicator of a change in the degrees of freedom of the system, and describes the distribution of energy flow among the ecosystem pathways (Heymans *et al*., 1997). Based on the description of *R* by Ulanowicz (2004), who suggested that "it strongly ties to the effective multiplicity of parallel flows by which medium passes between any two arbitrary system components". Redundancy is linked by Christensen (2005) with system stability and proposed by Heymans *et al*., (1997) as an index of foodweb resilience. According to Bondavalli *et al*., (2000) high redundancy signifies that either the system is maintaining a higher number of parallel trophic channels in order to compensate for the effects of environmental stress, or that it is well along its way to maturity. With regard to overall performance and robustness, ecosystem level indicators based on ecological network analysis and foodweb analysis are informative on intermediate and long time-scales (Curry *et al*., 2005, Moloney *et al*. 2005, IEEP 2005). But they are also difficult to use in annual updates and operational approach, and may be more difficult for stakeholders to understand (IEEP 2005). In addition, using food-web models and the ecological network analysis approach to explore different management scenarios, through simulation fishery and nutrients management, could deliver integrated overview on ecosystem level.

5.3.6 System omnivory index

The system omnivory index (SOI) measures the distribution of feeding interactions among trophic levels of food webs, thus SOI allows for evaluating the complexity and connectivity of food webs, that have been associated to ecosystems ability to recover from perturbation (Christensen, 1995). Given a food web with n elements, the SOI is calculated as the weighted average of the elements' omnivory, this latter calculated as the omnivory index (OI) . The OI of each consumer element i with trophic level TL_i is quantified as the variance of the trophic levels of its preys (TL_j) (Williams and Martinez, 2004). The SOI of a given trophic network is quantified as the weighted average of the OI of all consumers of the network, where the weighting factors are taken as the logarithm of each consumer food intake (Q_i) (Christensen and Pauly, 1993). This allows for accounting of the different strengths of consumer interactions and the logarithm is used on the observation that consumptions are approximately log–normally distributed within the system (Christensen and Pauly, 1993).

Topological configuration of links and their weights affect SOI altough it is quite robust to the number of nodes in the web (Libralato, 2013). Comparison of stability and complexity indices including SOI for coastal marine food webs, highlighted positive correlation between SOI, magnitude of change and recovery time , thus suggesting that SOI is inversely related to stability in the marine ecosystems analysed (Perez-Espana & Arreguin-Sanchez, 1999). Moreover, application of SOI and other ecological indicators on the basis of outputs of protected and fished marine food webs standardized by number of elements, suggest that SOI is sensitive to fishing (Libralato *et al*., 2010).

5.4 Structural Indicators linked to diversity and 'canary' species

Indicators that have been suggested in the workshop to relate to biodiversity in food webs or to highlight the fate of particular "canary species" (Link 2005) include scavenger biomass, geometric mean abundance of seabirds, productivity of key predators, a general Species Richness Index, and the Gini-Simpson diversity index (species dominance) of large fish and of small fish by biomass.

5.4.1 Guild Surplus Production models

Guild Surplus Production is tracked in the annual Ecosystem Assessment document for the North Pacific Fisheries Management Council (e.g.. Zador 2013). Species are grouped into functional guilds based on feeding and life-history studies. Survey and catch time-series for each species are used to calculate the surplus production for each guild. To use as a catch limit, in addition to a single-species limit for each managed stock, the sum of quotas for each guild cannot exceed the MSY for the guild as defined by a standard surplus production model. Per-species reductions to meet this overall limit are not proscribed by this index; reductions can be made for stakeholder or economic reasons. For Bering Sea (ecosystem-wide) indicator example, see Meuter and Megrey (2006). The indicator uses the same data collected for the individual species within each guild (survey biomass and catch).

5.4.2 Total biomass of small fish

This indicator uses survey catch biomass of predefined small (pelagic) fish to assess exploitation levels of commercial stocks. The amount of energy transferred from zooplankton to higher trophic levels by pelagic fish is ultimately limited by the biomass of pelagic fish available. Shephard *et al*., (2014) therefore suggest that both the biomass of individual stocks should be above precautionary reference points on average and the total stock biomass of all pelagic fish together should be above a joint community reference point. In practice, the community reference point is always reached when all individual stocks are above precautionary reference levels. However, in the case where one or more stocks are substantially below single-stock reference points, additional care should be taken in the exploitation of the remaining stocks in the area.

5.4.3 Proportion of Predatory Fish

Predatory fish species are defined as all surveyed fish species that are not largely planktivorous (i.e. phytoplankton and zooplankton feeders should be excluded, Shin *et al*. 2010). A fish species is classified as predatory if it is piscivorous, or if it feeds on invertebrates that are larger than the macrozooplankton category (.2 cm). Detritivores should not be classified as predatory fish. This indicator captures changes in the trophic structure and changes in the functional diversity of fish in the ecosystem. It is sensitive to fishing pressure, but since it is a ratio, it will also be subject to changes in non-predatory fish, whose biomass may vary for other reasons (e.g. environmental driver, Bundy *et al*., 2010).

This indicator is calculated as the biomass of predatory fish surveyed / biomass surveyed, and the data required are trawl survey data and food habits data (or if not available locally, from information in the literature, or from comparable systems).

5.4.4 Pelagic to demersal ratio

The ratio of pelagic to demersal fish (P:D ratio) obtained from fishery-dependent or -independent surveys is a commonly used metric that describes trophic energy flow and community structure (Caddy 2000, de Leiva Moreno *et al* 2000, Rochet and Trenkel 2003, Link 2005). Changes in P:D ratio have been linked to anthropogenic pressures such as fishing and eutrophication. Targeted fishing can result in notable shifts in this indicator, however, changes may be not be entirely clear, as an increase in the P:D ratio could be caused by an increase in pelagic fish or a relative decrease in demersal fish. As an indicator of food web properties, P:D ratio may overlap with other large and/or forage fish indicators, but does capture important trophic relationships.

5.4.5 Biomass of trophic guilds

Biomass of trophic guilds is a measure of ecosystem structure, estimated as the aggregate biomass of each trophic guild. Individually they provide a measure of the change in biomass of trophic guilds. Collectively used they provide a measure of change in overall structure. It can be applied to all marine species if the information is available, based on survey data or model results. Work to date has largely focused on fish trophic guilds (Shackell *et al*., 2012; Rochet *et al*., 2013), but could be extended to invertebrates birds, and marine mammals. Measures of functional diversity could also be developed using these data. Data sources can be from research surveys or models.

5.4.6 Lifeform-based indicator for the pelagic habitat

Ecosystem health theory (reviewed by Tett *et al*., 2013) suggests that ecosystem resilience, and the sustainability of services, depends inter alia on the abundance and relationships of non-substitutable `functional groups' or 'lifeforms'. The abundances and trophic structural relationships of phytoplankters, and their protozoan and mesozooplankton consumers, change seasonally. The Plankton Index (Pi) method takes account of such seasonality and requires the plotting of log-transformed lifeform abundances, based on at least monthly samples, in sets of 2-D state spaces (Gowen *et al*., 2011). These plots (Tett *et al*., 2008) often suggest a fuzzy doughnut. When the data relate to a reference period, an envelope can be drawn to include a fixed proportion (usually 90%) of points in this doughnut. Data from other years can be plotted against this envelope; the Pi[j,t] value (for lifeform pair j and year t) is the proportion of new points that fall inside the envelope. For a given value of t, values of Pi for different lifeform pairs can be averaged. A UK project has identified sets of lifeform pairs that may serve for assessment of environmental status in relation to COM (2010) criteria 1.4, 1.6, 1.7, 4.3, 5.2 and 6.2. The lifeform pairs relevant to Food Webs and criterion 4.3 are: (i) chlorophyll concentration and mesozooplankton abundance; (ii) phytoplankton >= 20 µm abundance and phytoplankton < 20 µm abundance; (iii) [adult] copepods >= 2 mm abundance and [adult] copepods < 2 mm abundance. Reference conditions for any of the Pi are expected to be dependent on ecohydrodynamic (EHD) conditions (van Leeuwen *et al*., ms). The UK is currently seeking EHD-specific references at sites in the Celtic or Greater North Sea MSFD ecoregions that are, according to expert judgement, in GES. Meanwhile, time-series of Pi will be generated from conditions during an agreed (but arbitrary) period of 3 years, and the time-series will be assessed for (a) significant trend, and (b) significant correlation with relevant pressures.

5.4.7 Region-specific indicators of abundance & spatial distribution,

Indicators can be selected to track the abundance and spatial distribution of major species which represent key community and or/ecosystem properties. Ideally, species representing different communities or habitats (benthos, plankton, fish, top predators) should be selected, in this way covering a large part of the ecosystem. As ecosystems are typically characterized by few strong links and many weak links among species or trophic levels, one (or few) indicator populations can describe broader ecosystem state and/or human perturbation. Criteria in the MSFD for selecting the groups/species that could be included in this category are those with fast turnover rates, groups/species that are targeted by fisheries, the habitat-defining groups/species, those at the top of the food web, and those tightly linked to other trophic levels (Rogers, *et al*., 2010).

5.4.8 Fish biomass/benthos biomass from models

Ratios are used to measure changes in community structure indicating the distribution of energy in the ecosystem. They are a supplement to biomass indicators and have the advantage that they do not reflect general increases or decreases in biomass in all components but only changes in the relative importance between the two groups. Hence, pelagic biomass/demersal biomass represents the balance between pelagics and demersals whereas the fish/benthos ratio reflects the proportion of the biomass which is diverted to benthos, including detritivores. The indicator captures changes in the trophic structure and changes in the functional diversity of the ecosystem. It is sensitive to fishing pressure, but since it is a ratio, it will also be subject to changes in non-manageable benthos, whose biomass may vary for other reasons (e.g. environmental driver, Bundy *et al.*, 2010). Data sources can be from research surveys (mainly nekton) or models (often benthos, since this is often not surveyed on appropriate spatial and temporal scales).

5.4.9 Zooplankton spatial distribution and total biomass

This indicator, which describes the distribution of zooplankton, is still at the developmental stage with methods, threshold and target value still to be developed. The reasoning for this indicator is that zooplankton constitutes an important link between primary producers and higher trophic levels in the food web. Zooplankton plays an important role in the energy transfer and nutrient cycling in the food web. The changes of the composition of the zooplankton community is coupled to environmental changes and can respond quickly to ecosystem changes. Zooplankton biomass and abundance can e.g. quickly respond to invasive species and local oil spills.

5.4.10 Scavenger biomass

Fishery discards provide food subsidies that help maintain fish and seabird populations and may allow some of these populations to be more abundant than they would be with just ambient resources (e.g. Polis and Strong, 1996, Link and Almeida 2002). Surveys of non-targeted scavenger biomass or abundance may provide an index of disturbance (Methratta and Link 2006, Link and Almeida 2002). Additionally, some scavenger species might be viewed as a "canary" or "iconic" species that can be used as an early warning of disturbance or fishing pressure.

5.4.11 Geometric mean abundance of seabirds

The indicator *Geometric Mean Abundance of Seabirds* is computed in regular intervals (e.g. yearly) as the geometric mean of the population sizes (e.g. numbers of individuals or breeding pairs) of those seabirds in the assessment region for which population time-series are available, normalized such that the indicator value at the beginning of the indicator time-series is one. The indicator is designed after the Living Planet Index (LPI, Loh *et al.* 1998, 2005), which now underlies Aichi Target 5 of the Convention for Biological Diversity. Modern indicator protocols take into account that species may enter or leave the set of species for which time-series are available, and that population sizes at low abundances become uncertain (Loh *et al.*, 2005, Buckland *et al.* 2011). Methods to compute indicator confidence intervals have been developed (Loh *et al.*, 2005, Buckland *et al.*, 2011). By its definition, the proportional rate of change of the indicator equals the average population growth rate of all populations contained in the indicator (here seabirds). Under conditions where populations fluctuate and turn over but overall biodiversity does not change, the indicator is expected not to deviate significantly from one. A steady decline of geometric mean abundance signals biodiversity loss. Seabird populations are known to be highly sensitive to food availability (Cury *et al.*, 2011), and their differentiation of foraging niches (Fasola *et al.*, 1989) is evidence of competition for food among them. Competitive exclusion resulting from loss of biodiversity among their marine resources (e.g. forage fish), or even at lower trophic levels (Rossberg 2013), can be expected to induce the slow decline of seabird diversity to which this indicator is designed to be sensitive. Geometric mean abundance of seabirds is therefore sensitive to a collapse of the pyramidal distribution of species over trophic levels in food webs (de Ruiter *et al.*, 2005).

5.4.12 Gini–Simpson diversity index (species dominance) of large and small fish by biomass

It is incompatible with GES to bring the foodweb into a state where only a few (large) predator or prey species dominate the system when the biomass of predators and prey was distributed more evenly in the system during the reference period. Species richness may be inadequate as an indicator as it often takes a long time to completely lose a species, while management should be informed and act earlier. The Gini-Simpson index (1-D) applied to the predator and/or prey community provides the possibility to detect unwanted changes in diversity. Simpson's Diversity Index is a measure of diversity which takes into account the number of species present, as well as the relative abundance of each species. As species richness and evenness increase, so does diversity (ICES, WGSAM, 2012).

5.4.13 Species Richness Index

Species richness measures the number of species within a community. A well-structured and functioning ecosystem will generally have many species; as a side effect of fishing, species richness may decrease (Rice 2000, 2003). However, as a food web indicator species richness may provide ambiguous information, since multiple community configurations may produce similar values (Rice and Gislason 1996, Gislason and Rice 1998). This was calculated as the number of species in any year whose numerical abundance or biomass was larger than some percentage of their value in a reference year. The IUCN Red List criterion of 20% was used as the reference value. Required data: species or functional group P/B, and species or functional group biomass/abundance to compare to refefence point.

5.4.14 The large fish indicator (LFI)

The Large Fish Indicator (LFI) is defined as the proportion by weight of large fish in the sample of a specified survey (SEC 2008, Greenstreet *et al*., 2011), where large fish are defined as those longer than a threshold length L_{th}, a region-specific threshold value. The value is chosen such as to optimize the responsiveness of the indicator to fishing pressure, as determined from historic data (Shepherd *et al*. 2011). The LFI takes no account of species identity but rather of individual sizes. However, it was shown to reflect mostly the proportion (by weight) of large-bodied species in communities (Shephard *et al*., 2012). Large-bodied species tend to be more vulnerable to fishing, which is why the LFI is sensitive (Greenstreet *et al*., 2011, ICES 2011, Shephard *et al*., 2013) and specific (Houle *et al*., 2012) to fishing pressure. Furthermore, by expressing the indicator in terms of proportions by weight, and not by numbers, and through judicious choice of the appropriate length threshold to define large fish, the indicator can be desensitised to variation in the abundance of small fish. The influence of environmentally driven recruitment events on indicator values can therefore be minimized (Greenstreet *et al*. 2011). Foodweb models (Shephard *et al*., 2013, Fung *et al*. 2013) and data (Fung *et al*. 2012) suggest that recovery of the indicator from pressures can be slow (decadal scale). The LFI, as an OSPAR EcoQO for the North Sea, is fully operational. It is part of the indicator suite that member states have to report on under the Data Collection Framework to evaluate the effects of fishing on the ecosystem (2010/93/EU). It was named as an indicator for foodweb GES (EU, 2010), and has been chosen as a common foodweb indicator by HELCOM and OSPAR (in some OSPAR Subregions as a priority candidate indicator).

5.4.15 Mean length of surveyed community

Mean length (ML) of all species caught in survey, whether fishery-independent, fishery-dependent, or as landings, can be a useful and simple indicator to evaluate the overall effects of fishing on an ecosystem (Bellail *et al*. 2003, Shin *et al*., 2005, Dulvy *et al*., 2004, Nicholson and Jennings 2004, Rochet and Trenkel 2003). ML quantifies relative abundances of large and small individuals and describes the size distribution of a community (Shin *et al*. 2005), and is relatively responsive to key pressures (Pauly *et al*. 1998, Link *et al*. 2010). ML is considered measurable and generally robust, however, the direction of response may be caused by increasing stocks of large fish or decreasing in stocks of small fish, leading to potential ambiguity. Whilst the metric is sensitive to fishing pressure, it can also be strongly influenced by environmentally driven recruitment events that introduce large numbers of small fish into the community (Badalamenti *et al*., 2002; Lekve *et al*., 2002; Wilderbuer *et al*., 2002).

5.4.16 Size spectra slope

Various measures of the change in size can be a useful indicator to describe composition of communities (Nicholson and Jennings 2004). Size spectrum slope measures the relationships between the biomass (y) of individuals within a body size class and body size (x), both normally plotted on logarithmic scales. Frequently a log to the base 2 transformation is applied to the body size class, particularly when weight classes are used so that each increase in body size classes represents a doubling in body mass. When applied to fish communities, the slope of the relationship becomes increasingly negative in response to fishing pressure; fisheries reduce the abundance of large sized fish, the direct effect of fishing, and as a consequence of reduced predation pressure from large fish, the abundance of small fish increases, the indirect effect of fishing (Rice and Gislason 1996, Gislason and Rice 1998, Nicholson and Jennings 2004; Daan *et al*., 2005). The size spectra slope is considered measurable and robust. However, the direction of response may not be entirely clear (Trenkel and Rochet 2004), as the steepening of the slope could indicate a decrease of large fish or an increase of small fish. The slope is particularly sensitive to changes in the abundance of small fish, which markedly affect the intercept of the regression line, as such the size spectra slope can be influenced by environmental driven recruitment events, which raise the abundance of small fish (Badalamenti *et al*., 2002; Lekve *et al*., 2002; Wilderbuer *et al*., 2002).

5.4.17 Zooplankton Size-Biomass index

This is a zooplankton indicator reflecting both mean individual size and total biomass of zooplankton community. The indicator represents food web capacity to sustain fish feeding conditions and exert grazing on primary producers. The rationale is that both mean body size in the community and total community biomass are positively related to fish feeding conditions, whereas total biomass alone is just representative of grazing pressure and trophic transfer efficiency (Stemberger and Lazorchak, 1994; Fuchs and Franks, 2010). The effects of zooplankton community structure on energy transfer and food web resilience have been demonstrated in both freshwater and marine systems (Lougheed and Chow-Fraser 2002; Kane *et al*., 2005; Jeppesen *et al*., 2011). The index is currently considered as a core indicator for the Baltic Sea (HELCOM 2012, 2013). In semi-enclosed seas, such as the Baltic Sea, with strong salinity and temperature gradients, no single zooplankton group can adequately reflect community properties

(Remm 1984), hence the need for this two-dimensional index. The index value decreases with increasing fishing pressure. Protocols for indicator assessment have been developed by HELCOM Zooplankton Expert Network (ZEN) using nine long-term monitoring datasets in the Baltic Sea (HELCOM 2012, 2013). In all datasets, the indicator was found to predict deviations from GES conditions. Determination of GES boundaries for the indicator is straightforward and based on the regional basin-specific Environmental Quality Ratios for chlorophyll accepted within Water Framework Directive and weight-at-age for zoo-planktivorous fish (HELCOM 2012, 2013).

6 Application of agreed evaluation criteria to proposed Food Web Indicators

6.1 Applying Selection Criteria

The indicator evaluation criteria noted in Section 3 (Table 3.1), grouped into five broad themes, were used to evaluate the full suite of FooWIs (Table 5.1; section 5).

6.2 Using Selection Criteria

Each indicator presented under Section 5 (Table 5.1) was evaluated against the selection criteria and scored as either 0, 1 or 2, where 0 = not met, 1 = partly met, and 2 = fully met. We used a Delphic method whereby sets of indicators were scored by small groups based as far as possible on consensus, following a discussion and common understanding of the indicators themselves and how to apply the criteria to the indicators. These were then examined individually and in plenary so that all scores were adjusted based on consensus-based discussions. We recognize there are other methods for arriving at these scores, but this approach was amenable to this particular working group structure.

Each of the 13 subcriteria was scored equally and no weighting was applied. Particular issues or concerns with individual scores were highlighted for subsequent discussion in plenary.

Scores were presented as a %age of the total score available (max score x number of categories; i.e. 2 x 13 = 26). Indicators were ranked within the agreed Attributes of food webs (Functioning (energy flows), Resilience (ability to recover from perturbation), Structure (species organization)).

The outcome of the scoring system was discussed and agreed in plenary before being used to inform the process of indicator prioritization and Roadmap development.

6.3 Challenges and Observations concerning application of the Selection Criteria

Although the scoring system provided a quantitative basis from which to select indicators, there was opportunity to allow for human judgement and other qualitative considerations when making the final selection.

Scoring outcomes were specific to the indicator as currently used and understood by the presenter. A different set of scores could have materialized if the indicator was applied to a different ecosystem component and for which data were less readily available.

A low score for an indicator was not necessarily a poor outcome. It suggested either that there were difficulties with the theoretical basis or applicability of the indicator in the context for which it was applied, or that the indicator was a good one but required more time to fully evaluate before putting into operational use.

7 Selection of appropriate food web indicators

The ranked indicators (Table 5.1) within the three food web attributes were evaluated in plenary to confirm the scoring so that priority indicators within each attribute could be identified. In the process, indicators were annotated to support and justify their position or to add further context and explain why scores were lower than perhaps expected. This annotation is used to support the discussion of the prioritization below.

It was clear that the group of functional (section 5.2.1 to 5.2.17) and resilience (section 5.3.1 to 5.3.6) indicators were generally applicable to D4 (food webs) and to some extent also D3 (fish communities). This suggested that the opportunity to provide guidance on this suite of indicators remained firmly within WKFooWI. In contrast, those allocated to the 'structural' category (section 5.4.1 to 5.4.17) were also appropriate to other descriptors of GES, especially D1 (biodiversity), D5 (eutro), D3 (fisheries) and D6 (*sea floor integrity*). As a result WKFooWI felt that it would be most appropriate to provide an opinion on which of the structural indicators scored most highly against the food web criteria. WKFooWI also felt that, without a fundamental review of the biodiversity attributes applied for indicator selection in D1, it was unlikely that specific structural biomass/abundance metrics required to support food web indicator development would be generated under this Descriptor.

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

The final rank scores were obtained from the unweighted sum of all 13 evaluation criteria. When the evaluation was re-run separately using just the first six criteria (linked to practical aspects of indicator measurement), and the next seven criteria (linked to aspects of indicator implementation), there was relatively little difference in the final overall outcome. This suggests that the final rank score was robust to variability of criteria selection and was little influenced by single criteria evaluations.

The following section highlights those indicators that scored highly against the criteria applied by WKFOOWI. A concluding section adds general context in preparation for the Roadmap to take forward indicator development in a management context.

7.1 Indicator appraisal: Food web function

A relatively large number of indicators were identified which had clear links to functional aspects of food webs. Those scoring highly against the assessment criteria are described below, and comments are also made in relation to those which did not score well.

7.1.1 Productivity (production per unit biomass, including seabird breeding success)

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, removal of key species by harvesting, or disruption of distributional overlap between predators and prey through climatic factors. This indicator class scored highly and showed promise to guide further development of specific food web indicators.

7.1.2 Total Mortality (Production:Biomass ratio)

This indicator is also known as Total Mortality Z (Fishing mortality + natural mortality) and commonly used in the ecosystem modelling community (Ecopath with Ecosim). Despite the relatively high score it was considered that this was not the most easily interpretable indicator of food web functioning. However, its inverse, (1/Z) is an estimate of longevity, which could be considered an indicator for resilience.

7.1.3 Primary Production required to sustain a fishery

It was considered that this indicator has a solid conceptual basis. . 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 are 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 lack of data to systematically estimate TE. Yet this indicator was viewed as more integrative of a wider suite of factors and the TE was considered a more minor (and simulation studies have shown robust for estimates of PPR) part of this overall indicator due to its broader inclusion of other factors.

7.1.4 Productive pelagic habitat index (Chlorophyll fronts)

Monitoring intermediate marine productivity and chlorophyll-a fronts by satellite using remote observation was considered an effective indicator of energy-flow in food webs. Indices such as this, which describe primary production and fuelling of the food-web, are thought to be particularly important to describe functional processes. There are limitations to their application mostly in the presence of coloured dissolved organic matter such as in turbid waters (e.g. Baltic Sea) for which a correction on chlorophyll-a content needs to be applied. Besides the monitoring of eutrophication, the implications for management are not always clear. Fronts are hydrodynamic features which attract significant biomass of commercial fish so there is potential to support fisheries management.

7.1.5 Ecosystem exploitation (fisheries)

This indicator 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.

7.1.6 The suite of marine trophic level indicators

Four fairly similar indicators of this type were evaluated, the mean trophic level of the catch, the mean trophic index of the fish community, the mean trophic level of the community and the trophic balance index. Each has slightly different formulation but all require a) good quality, and regularly updated data on dietary relationships, b) time-series of survey catch or landings from broad regional seas to avoid local population or fleet effects, and c) accurate and agreed, regularly updated assessments of trophic levels.

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

TL indicators integrate across the ecosystem. They are likely to be applied in some sub-regions where data are considered suitable.

7.1.7 Other low scoring functional indicators

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 rigour) and the likely ease of implementation. However, some may warrant further investigation.

7.1.8 Indicator appraisal: Resilience Indicators

Resilience is an important attribute of food webs and the grouping process was used to highlight those indicators which most closely corresponded to this attribute.

It was interesting to note that the six indicators that had a link to the functioning attribute, and also contributed to the inherent resilience of the food web, were generally scored lower than many other indicators. This may be because they are more conceptually complex.

It was considered that the top three in this category, the Mean 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 WKFooWI felt that these would not be recommended as suitable for implementation in the short term. The complexity 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 science credibility. The criteria with low scores, e.g. the costs of dietary sampling, highlight where most effort needs to be directed in future in order that these indicators can become more fully developed. For example, it would be easy to address some of the communicability issues and other criteria where these scored low.

The indicators that scored poorly in this attribute (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, which have not been made widely available even to support applied multispecies fishery assessments.

The group was aware of other indicators that might inform the resilience of food webs but was not made aware of them in time to review them. It is possible that some, such as the mean lifespan and the mean maximum length (longevity) weighted by number or biomass of a population would score highly.

7.2 Indicator appraisal: Structural Indicators

Several indicators in this category resulted in relatively high scores, suggesting that managers may want to use these indicators to help interpret patterns observed particularly in 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 as well as structure of the individual components.

It needs to be made clear that many of these structural indicators are describing the same ecosystem components in multiple different ways, and other EU Directives, as well as other Descriptors of GES, are already leading on developing these indicators. Therefore the data are likely to be collected and available.

7.2.1 Guild-level biomass across ecosystem components

Valued indicators were those which informed trends in absolute biomass, production, or ratios of both, for a number of ecosystem components especially higher 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. 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 index (a species dominance index of large fish and of small fish by biomass) and the Species Richness Index were thought to be potentially useful for assessing food web resilience.

7.2.2 Validity of Results

Group scoring processes are naturally dependent on group composition. Hence, a different group of scientists may come to different results, leading to different scorings of different indicators. This can potentially invalidate the general applicability of both the level of the indicator scoring and the ordering of the indicators according to scoring, presenting serious problems for the general validity of the results. To investigate the extent of this problem, the group scorings of WKFOOWI on a previously examined subset of FooWIs were compared to the scoring of WGSAM (ICES, 2013) where the two groups scored the same indicators. Though there was some minor overlap in membership of the two groups, only one person participated in the scoring of both groups, and hence the validity was not a result of this effect. The comparison showed that indicator order was remarkably consistent (fig 7.2.2), whereas indicator scoring varied between group with WKFOOWI generally providing a wider range of scores then WGSAM. This indicates a high consistency of the indicator ordering but a lower consistency of scoring level. Hence, indicators should not be disregarded based on their scoring level, but the ordering of the indicators can be taken as indicative of a general perception of the ICES scientific community.

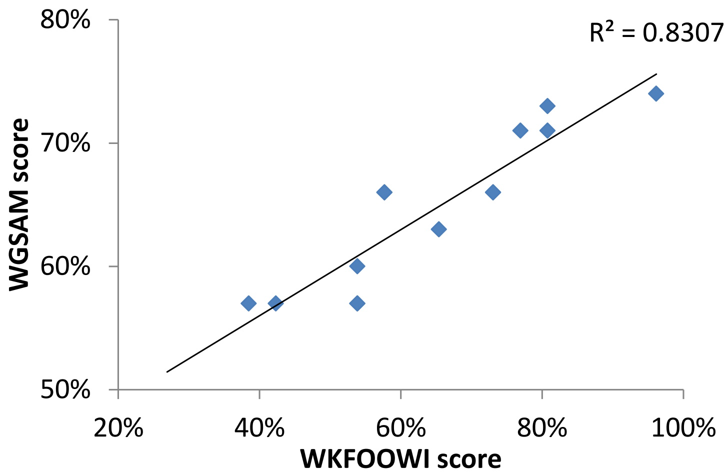

Fig. 7.2.2 Comparison of WKFOOWI scoring and WGSAM scoring.

8 Roadmap highlighting process for further development of indicators where necessary

While it is possible to make broad conclusions about specific indicators or indicator classes, their applicability still depends on the availability of suitable data at a regional sea or Member State level, and the willingness of national administrations to apply the indicator in a management context. Most effective regional seas management will be achieved when member states sharing management responsibility reach common agreement on suitable metrics and targets / reference points. This is likely to require compromise, and there is a significant role here for Regional Seas Conventions to support indicator development.

The other important part of this cooperation will be the selection of a suite of indicators that together act to support coordinated management action. Working with existing legislation, where there are already effective food web indicators in development, will simplify the task significantly.

The suite of suggested FooWIs evaluated above is the outcome of the application of selection criteria at a regional seas scale. It is possible that in a subregional assessment by a member state there would be local factors that change priorities. The outcome here does not therefore preclude work on other FooWIs, though the extent to which they are broadly applicable in a regional context should be assessed.

The criteria that scored relatively poorly can be used as a ready means to identify the extent of further work required. In several areas, particularly for communication, there is scope for rapid improvement as part of the ongoing work to improve the rigour of the indicators identified.

Within regional programmes to further refine food web indicators, WKFooWI supports the use of an assessment process such as the one used here that takes account of multi-criteria in a full assessment. As described above, the criteria for indicator assessment are readily available and sufficiently robust to be applied with confidence in a range of situations.

This would be a useful activity by the Regional Seas Conventions in local coordination of food web indicator development. WKFooWI suggest a repeat of this broad scale evaluation in about 2 years to evaluate those indicators that require further development.

WKFooWI noted on several occasions that there were significant links between some of the MSFD descriptors. While the group is clear about the priorities for current food web indicators application, and future work thereon, it also recognizes that some indicators that provide important context, i.e. structural indicators, are the responsibility of other groups. WKFooWI suggests that similar broad scale review is undertaken for these groups, especially for biodiversity, fish community, and sea floor integrity (D1, D3 and D6), with strong links made to the outcome of WKFooWI. WKFooWI also underscores the need for good communication between the groups working on the eleven MSFD descriptions, both in the selection of indicators and their interpretation.

8.1 . Choosing Suggested Indicators

WKFooWI suggests two sets of indicators, one set that may be implemented now and one that holds promise for future development. Key considerations that went into our choice of suggested FooWIs included:

Relative ranks within the major FooWI attributes informed the choice of indicators, but were not adhered to in a rigorously quantitative manner.

Coverage of all attributes—we wanted to ensure, to the extent practicable, that all three main categories of FooWI attributes were represented.

All functional groups—we attempted to maximize the 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 classes—we wanted to ensure the major classes of FooWIs were represented, not necessarily all of them, but those were deemed by this group and others as important facets to elucidate food webs.

Current operability— effectively this was an *ad hoc* review (or perhaps weighting) of operability issues related to data availability, management relevance and existence of thresholds, targets or related reference points, which although were selection criteria, were deemed critical enough to warrant additional consideration. These were applied only for the current set of suggested FooWIs.

Links to other MSFD Descriptors—this consideration was not used to omit or choose any particular indicator, but was used to ensure that we emphasized those FooWIs that are unique to this MSFD Descriptor. We wanted to ensure that particularly those elements associated with food webs (e.g., integrative, resilience, etc.) were at least covered by some part of the suggested indicator suite.

8.1.1 Suggested FooWIs for Current Use

8.1.1.1 Guild level biomass (and production)

This (or if a set, these) addresses structural attributes of food webs, and can also serve as a proxy for functioning. It was noted that the typical use of this type of indicator has been for fish, but if feasible this indicator should include multiple guilds across the trophic levels, such as primary producers, zooplankton, benthos, and charismatic megafauna, beyond just fish or upper tropic levels. The guilds should be determined as appropriate to the taxa in the regional seas.

This indicator more clearly specifies the MSFD D4 indicator, Production per unit biomass 4.1.1 as well the D4 indicator abundance within range 4.3.1. It was recognized that in some subregions, production may not be available, so biomass would be feasible. Yet biomass of species guilds was deemed highly useful in its own right, and if both are possible that both should be considered.

8.1.1.2 Primary Production Required to sustain a fishery

This addresses the functioning attribute of food webs. It is understood that PPR is really PPR to sustain a fishery, and is thus a measure of the ecological footprint of the fishery. However, this metric can, and often does, integrate a wide range of removals from a food web. It was also noted that derivatives of this FooWI could, where feasible, be contrasted to estimates of primary production to ensure it is directly appraised against field data. This indicator more clearly specifies the prior D4 indicator, Production per unit biomass 4.1.1. It was recognized that 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 this attractive, integrative, and more feasible to estimate than is often perceived.

8.1.1.3 Seabird (charismatic megafauna) productivity

The breeding success of seabirds addresses the structural and functional attribute of a food web, and although multiple views were expressed on the point, can also serve as a proxy for resilience as well. Although particular to seabirds, especially breeding success/ chicks per pair, it was recognized that such taxa may not be prominent or as important in all regional seas. Thus the WKFooWI members also noted that this productivity indicator could also been calculated for marine mammal taxa (i.e. pup production rates). This indicator more clearly specifies the prior D4 indicator, Production per unit biomass 4.1.1.

8.1.1.4 Zooplankton size biomass index

This addresses both structural and functional attributes of food webs. This indicator was identified as important to include because although indicators associated with this taxa group were often ranked lower, they represent an important part of the food web, being the link between lower trophic level primary production and upper trophic level consumption and growth. Further, in many food web studies measures of keystoneness quite typically have at least some major group of zooplankton as one of the most important taxa groups. The specific indicator should be one that integrates across the different facets noted in the title, but which particular one is context dependent for a given regional sea.

8.1.1.5 Integrated trophic indicators (mean TL, mean size)

This addresses both structural and resilience attributes of food webs. WKFooWI members noted that 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 one could utilize for this category, but something such as mean trophic level, or mean / proportion at size of the community (which have all been shown to be correlated) depending upon trophic data availability in a given regional sea.

It was noted that all of these suggested FooWIs would need to be informed by, and potentially be interpreted from, indicators collected and developed in other MSFD descriptors. The important point being that certain taxa groups need to be covered, regardless of what descriptor they occur within. Aggregate measures of phytoplankton, zooplankton, forage fish, scavengers and birds were deemed important for D4 FooWIs.

8.1.2 Future development of FooWIs

WKFooWI suggests the following FooWIs as promising to consider and develop for use in the future. These may require that the science warrants further development, but more likely that these need to have broader data availability or infrastructure to support data in a broader set of regional seas, better links to management, or clearer thresholds. It does not imply that other indicators may not be worth pursuing or that these will necessarily develop into viable candidates; rather that these appeared promising in the WKFooWI evaluation. However, the rigour of their estimation, their response to pressure, their behaviour and the estimation of reference points generally need to be further explored.

8.1.2.1 Ecological Network Analysis

The broad set of Ecological Network Analysis-derived indicators were identified as potentially useful. Some of the more complicated indicators that have been extant for multiple decades (e.g. cybernetic instances such as those posed by Ulanowicz *et al.*) may not be worth further pursuing. But others are being identified, merit further testing, and warrant further consideration. An example could be overall mean transfer efficiency. These were not quite ready for management, but demonstrate promise to cover an integrated food web perspective addressing multiple food web attributes, particularly resilience.

8.1.2.2 Gini-Simpson dietary diversity index

The Gini-Simpson dietary diversity index (and related diet diversity and energy flow indicators) was also identified as potentially useful. The major concern was widespread and routinely collected data availability of diet or food habits data. The major advantages were its intuitiveness and that it addressed a full range of energy flows.

8.1.2.3 Condition Indicators

A broad class of Condition Indicators were identified as nearly ready. These are represented by mean weight at age and similar, but were viewed as important functioning FooWIs. They were very ready scientifically and often had clear thresholds, but did not always have widespread data availability.

8.1.2.4 Marine Trophic Level indicators

A broad class of Marine Trophic Level indicators was noted as being promising to better elucidate resilience attributes of food webs. There are many specific examples of these indicators, and further development, particularly regarding testing relative to pressures, was deemed a promising approach. These would particularly be informative for food web resilience attributes.

8.1.2.5 Primary producers

There as a general consensus that more information regarding primary producers would be useful for D4. Certainly other MSFD Descriptors could consider this set of indicators, but they are informative for D4. An important consideration is that satellite derived chlorophyll front data, and estimates of primary production, are widespread and available. A particular indicator that WKFooWI evaluated that held particular promise was the Productive pelagic habitat index. It and others like it hold promise, but require further development of management linkages and thresholds.

8.1.2.6 Zooplankton Indicators

Although some are extant now, the broad class of Zooplankton Indicators was noted as important, needed and simply requiring further development—largely in terms of familiarity, thresholds, and clearer management linkages— before usage. However, the WKFooWI members noted that even if management relevance is never directly linked, these indicators would still be important to consider and develop given the importance of this taxa group to the food web.

8.1.3 Other Considerations for Future Indicator Development

Apart from the obvious infrastructural, data, and related needs, and given the usual scientific testing and rigor checking associated with indicator development, two overarching factors should also be considered in future development.

WKFooWI reiterated the need to better evaluate food web resilience. The WKFooWI noted that resilience is a more nuanced attribute that in some ways combines structural and functioning attributes, but in such a way as to be uniquely informative. Therefore, refined evaluation of resilience indicators, using existing FooWIs in light of how they have been considered to inform resilience elsewhere, and explicit evaluation of other resilience related indicators, should be considered in future indicator development efforts.

Generally speaking, the development of thresholds or targets warrants further attention. FooWIs may be interesting scientifically and relevant to management, but if they cannot inform management action they have less utility.

8.1.4 Protocols to Evaluate future FooWIs (and other indicators)

WKFooWI recommends that future evaluation follow this general process presented herein. The approach noted represents best practices for indicator selection and builds upon a wide range of previous ICES and global bodies of work. It also affords the opportunity to examine how previously emphasized D4 FooWIs have changed relative to a broader suite of indicators.

The suggested protocol would consist of the following steps:

- Brief review of criteria available, but largely using that described in this and related ICES (WGBIODIV, WGECO, etc.) and other indicator work.
- New indicators are presented, and already-examined indicators be updated.
- The new set of candidate indicators are scored using a multi-criteria decision analytic approach as used here and elsewhere.
- The method for consensus of scoring may vary, but the important point is to ensure consensus in a transparent, collegial and objective manner.
- Any future updates or advances particularly emphasize the development of thresholds for any possible indicator, to the point that those without demonstrable and tested targets largely be omitted, with few exceptions.

Examination of the criteria in Table 3.1 will identify facets of FooWIs that require further attention. We highlight the four most probable areas for improvement. One area would be data availability and quality which requires enhanced infrastructure to obtain and process the necessary data. Of particular note, it would be wise to invest in routine (even if albeit infrequent) food habits / diet sampling, as that is a core element for many of these food web indicators and has wide application elsewhere.

Another area for reasonable improvement would be to better link response indicators to pressure indicators and thus solidify the scientific underpinning for why indicators could be used. Without understanding the pressure-response nature, especially if it includes non-linearities, the utility of food web indicators will remain marginal (Shin *et al.*, 2012).

The third area for probable improvement would be to better associate indicators to management relevance and particularly to demonstrate responses to management action. A range of simulation studies may be warranted for this point.

The final area for improvement would be better delineation of indicator thresholds. This point is discussed further below.

8.1.5 Protocols to establish more rigorous thresholds for FooWIs (and other indicators)

Indicator response must be related to measurable pressure(s) (i.e., anthropogenic or environmental pressure) that are based on causal or otherwise robust relationships. Methods to identify thresholds seek to identify a point or level at which a small change in pressure results in a large, and sometimes abrupt, response in attribute state or function have been developed in a variety of fields (e,g., ecotoxicology; Suter, 1993 and econometrics; Zeileis and Kleiber, 2005).

We note that WGECO developed related criteria to evaluate indicator targets. The criteria cover: the approach to define targets; framework consistency; regional consistency; preference for established targets; integrity; adaptability of targets; uncertainty in target estimates; derivation of targets; scale; cross-sectoral integration and trade-offs; and ease of understanding (ICES-WGECO 2013). WKFooWI builds upon this, but provides particular emphasis on the means to define the targets, while the other WGECO criteria reinforce facets of the selection criteria previously noted.

In general, thresholds detection processes adhere to the following framework (Anderson *et al* 2005). A measurable attribute of change must be identified between the response and pressure variable(s) such as the variance, mean, or slope. Additionally, change in these attributes can also be examined over time to explore regime shifts or other temporal patterns (Fewster *et al.*, 2003). Multiple analytical methods, such as cumulative sums (CUSUM; Hinkley, 1970), sequential t-test (STARS; Rodionov, 2004), empirical fluctuation processes (Zeileis and Kleiber, 2005), and significant zero crossings of piecewise regression models (Samhouri *et al.*, 2012) or generalized additive models (Large *et al.*, 2013) have been used to identify the level of pressure that results in a significant indicator response (Anderson *et al.*, 2005). When available, simulation modelling can also be used to explore the management implications of empirically determined thresholds, which may offer further insight into management utility of indicators (Fay *et al.*, 2013).

8.2 Timelines

Awareness of indicators suggested for current use (section 8.1.1) should be encouraged within the next few months as Member States prepare their MSFD monitoring plans. Beyond that, ongoing review to fit with the six year review cycle of the MSFD would be appropriate, as well as any planned revision of the Commission Review Document. Under these circumstances, WKFooWI would be keen that key messages on food web energetics described in this report are transmitted to other groups developing and revising other descriptors, especially those related to biodiversity.

There is an important role for the Regional Seas Conventions in leading this process, particularly in light of the broad scale processes that are included in food web assessment.

9 Recommendations

WKFooWI members make the following recommendations:

1. That in the short term for the specific MSFD D4 context, these indicators be considered for application at a Regional Seas scale.

Primary production required to sustain fishery

Seabird (charismatic megafauna) productivity

Zooplankton indicators based on community biomass, size structure and productivity.

Integrated trophic indicators (mean TL, mean size)

Biomass of trophic guilds

2. That in the medium-term future (i.e. 2–3 years), a similar *ad hoc* expert group, or an existing ICES WG, re-evaluate FooWIs and how they have developed. Suggestions for specific areas of development have been included in this report.

3. That appropriate organizations commit to the necessary infrastructure to, as appropriate, collect, process, manage and analyse requisite food web related data at a regional and subregional seas scale. This includes data on primary production, zooplankton, scavengers, forage fish, seabirds, and, importantly, food habits.

4. That ICES adopt the general approach here as a best practice and thus avoid (what is perceived as) endless and needless re-evaluations of indicator selection criteria, so that future work can emphasize an objective evaluation of indicators, and not a recapitulation of their attributes or criteria.

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Workshop on Food Web indicators 31 March- 3 April 2014 (WKFooWI)

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Annex 2: Agenda

Monday, March 31

0900–0930 Greetings, Introduction, Expectations of Workshop

0930–1100 (TOR C, D) Discussion of Policy and Management Needs for Indicators (MSFD, ICES context, national ocean policy, food web science overview)

1100–1115 Morning Coffee/Tea

1115–1230 (TOR B) Presentations on approaches to Indicator Review Criteria

1230–1330 Lunch

1330–1500 (TOR B) Discussion and agreement on Indicator Review Criteria

1500–1515 Afternoon Tea

1515–1730 (TOR D) Presentations and Discussion on generic Indicator Responses, Thresholds

1730 Adjourn

Tuesday, April 1

0900–0915 Logistics, Recap prior day

0915–1000 (TOR C) Discussion on Using Food Web Indicators for MSFD and in other Marine Ecosystem management contexts

1000–1100 (TOR A) Presentations on Food Web Indicators

1100–1115 Morning Coffee/Tea

1115–1230 (TOR A) Discussion of Food Web Indicators

1230–1400 Lunch

1400–1600 (TOR A) Presentations on Food Web Indicators

1600–1615 Afternoon Tea

1615–1730 (TOR A) Discussion and tabulation of proposed Food Web Indicators using agreed Criteria

1730 Adjourn

Wednesday, April 2

0900–0915 Logistics, Recap prior day

0915–1100 (TOR C) Evaluation/Selection of operational Food Web Indicators

1100–1115 Morning Coffee/Tea

1115–1230 (TOR C) Evaluation/Selection of operational Food Web Indicators

1230–1400 Lunch

1400–1600 (TOR D) Discussion of Roadmap highlighting process for further development of indicators where necessary

1500–1530 Afternoon Tea

1530–1730	(TOR D) Develop Roadmap outline
1730	Adjourn
1900	Group Dinner

Thursday, April 3

0900–0915	Logistics, Recap prior day
0915–1100	Writing session
1100–1115	Morning Coffee/Tea
1115–1230	Writing session
1230–1400	Lunch
1400–1500	Writing session
1500–1600	Final discussion, wrap up
1600–1615	Afternoon Tea
1615–1730	end

Annex 3: WKFOOWI terms of reference

WKFooWI - Workshop to develop recommendations for potentially useful Food Web Indicators

2013/2/ACOM49 The ACOM Workshop to develop recommendations for potentially useful Food Web Indicators (WKFooWI), chaired by Stuart Rogers* (UK) and Jason Link* (USA), will meet 31 March – 3 April 2014 at ICES HQ, to:

1) Review Pragmatically Estimable Food Web Indicators
2) Evaluate said Indicators Against Standard Criteria for Indicator Use
3) Develop a proposal for food web indicators for marine ecosystem based management incl. relevant to the Marine Strategy Framework Directive (MSFD)
4) Suggest and plan the way forward (i.e. preparation of a roadmap how to get there)

WKFooWI will report by 1 May to ACOM.

Supporting information

Priority	High.
Scientific justification	There is a well established need to use food web indicators (structure and function) in the management of marine ecosystems, and the management of the components in those marine ecosystems. Many typical metrics used to manage marine ecosystems and living marine resources are indicative of state variables and structural properties (e.g. biomass); as such they often miss many of the key features, dynamics and properties of marine ecosystems that can lead to biased or mis-informed management advice. Food web indicators better and more directly represent measures of rates, networks features, connectivities, and functioning of these marine ecosystems and living marine resources. As such they can provide augmenting information pertaining to Good Environmental Status. In the light of the EC Marine Strategy Framework Directive there is an urgent need for operational indicators for food web structure and function, that can be used to advice management of human activities in the marine ecosystem and monitor the response of the system towards Good Environmental Status (GES). Tor c and d. The EC has requested ICES to develop a proposal on indicators for descriptor 4 of MSFD (food webs). As stated in the Commission Decision (20010/477/EU) additional scientific and technical support is required for the further development of criteria and potentially useful indicators to address the relationships within the food web. In this framework, ICES shall work towards recommendations for potentially useful indicators(to be considered for the revision of the Commission Decision) with a roadmap how to get there.(**DG ENV request 1d**)
Resource requirements	None. The research programmes providing input to this WK are already underway and resources committed. The additional resource required for the WK is negible.
Participants	Approximately 25-30 experts with interest in suggesting and applying indicators on foodweb structure and function.

Secretariat facilities	Two meeting rooms at ICES HQ
Financial	No extra funding requested.
Linkages to advisory committees	This work will feed directly into the work byACOM, and support the ICES Council Steering Group on the MSFD.
Linkages to other committees or groups	WGECO, WGSAM,and the groups under the RSP of ICES.
Linkages to other organizations	EC and the EU Member States, the Regional Seas Commissions in Europe (e.g. OSPAR and HELCOM) EEA, NOAA, PICES, ESSAS, IMBER, IOOS

Annex 4: Technical Review of Indicators for MSFD Descriptor 4

Summary of reviews of WKFooWI and WGECO

This document is a synthesis of the independent reviews of the work of WKFooWI and the work of WGECO in readiness for the drafting of ICES advice. WGECO also commented on the work of WKFooWI, and this is included in this synthesis.

Overall summary

The reviewers appear content that the indices were evaluated appropriately and using suitable criteria. There was some criticism of the inadequate descriptions of each index. One reviewer felt that the definitions of structure, function and resilience need clarification and that indices were perhaps inappropriately classified. The issue of indices for management action and indices for surveillance of change (no direct pressure to state relationship, e.g. zooplankton biomass index) was discussed and needs to be highlighted. This should be clarified for each of the five in the suite of 5 proposed indices. The suite of 5 was broadly accepted by the reviewers although one reviewer proposed that two other types of indices were missing (structural foodweb index for uni-cellular organisms and a topological index (who eats who). There was criticism of the roadmap (with an alternative roadmap provided), especially for the development of targets or thresholds. There was a request to make sure that the advice links through to the previous ICES advice on DCF time-series for the MSFD.

Little extra insight was provided about the LFI work by the reviewers. Considering that the LFI is included in the MSFD legislation, and appears to now be moved from D4 to D1 by the scientific community, neither WKFooWI nor WGECO concisely addressed what the MSFD should do with the LFI.

1. Foodweb indicator development carried out at WKFooWI

1.1 WGECO comment

WGECO noted that WKFooWI recognized the following key elements of a process for choosing indicators:

- The need to have a suite of indicators, and not just the "one" indicator;
- The need to have clear criteria for selecting indicators;
- The need to have clear objectives for why indicators shall be developed and used;
- The need to have clear venues for evaluating, vetting and referencing indicators;
- The need to have clear "clients" who will use the indicators and are asking for them.

In addition, indicators should be sensitive, have a basis in theory and be measurable. The evaluation criteria were availability of data, quality of underlying data, conceptual/theoretical basis, communication and manageable. WKFooWI distinguished the attributes of a foodweb characterized by an indicator (structure, function, resilience) and what they called a foodweb indicator class (energy flow, network, canary, diversity, size, aggregate). It is also important to consider functional groups (phytoplankton, zooplankton, benthos, cephalopods, fish, birds, mammals, reptiles). WGECO then provide a table of which potential indicators were primarily associated with which foodweb attributes (WGECO Table 3.1). WGECO agreed that the evaluation of the indicators was carried out following the accepted methods developed by WGECO and WGBIODIV.

WGECO made the following observations about the five indicators recommended by WKFooWI as the initial suite of indicators.

INDICATOR	RATIONALE	WGECO OBSERVATION
Guild level biomass (and production)	Structural attributes of foodwebs, and can also serve as a proxy for functioning. Improved specification of MSFD D4 indicator, Production per unit biomass 4.1.1 as well the D4 indicator abundance within range 4.3.1.	This would definitely be useful as a surveillance indicator[1] for the state of the foodweb and the relative stability of its major components. As an operational indicator, it may be difficult to manage, particularly through fishery measures. Given our current state of knowledge, it may also be difficult to set specific targets for the biomass of particular guilds. If management were possible, it may well end up with a focus on particular species within a guild where fisheries measures might be more effective.
Primary Production Required to sustain a fishery	The functioning attribute of foodwebs. Improved specification of D4 indicator, Production per unit biomass 4.1.1.	This would appear to be primarily useful as a surveillance indicator[1]. It is difficult to see how specific management could be exerted. If trophic level of specific groups is not constant, the indicator requires persistent sampling of diet composition. It requires context setting and can be difficult to communicate.
Seabird (charismatic megafauna) productivity	The structural attribute of a foodweb, and may be able to serve as a proxy for resilience or functioning. Improved specification of D4 indicator, Production per unit biomass 4.1.1	These indicators have already been well documented and used in a range of contexts, and can be considered as operational and suitable for management. In the full version of the WKFooWI report, seabird productivity is directly cited as expressing the "abundance" of forage fish, while it actually probably reflects the "availability" of these fish. These indicators are undoubtedly valuable in themselves, but maybe questionable in terms of "integrating" the foodweb below them.
Zooplankton spatial distribution and total biomass	Both structural and functional attributes of foodwebs.	This would be a surveillance indicator[1], for general ecosystem health and productivity–but would not be manageable.
Integrated indicators (mean TL, mean size)	Both structural and resilience attributes of foodwebs.	Again, this is a good surveillance indicator. Like guild level biomass, it may be potentially subject to management that focuses on individual components of the community

WGECO then stated that the most valuable indicators are those which are operational and appropriate to direct management via a pressure–state relationship. There are also surveillance indicators that are indicators that quantify neither pressures nor directly affected attributes, but are nevertheless needed for an informed assessment and management of foodwebs. A key feature of surveillance indicators is that they are unlikely to respond unequivocally to management or support target setting. They operate more to provide warning of changes that may impact on our ability to achieve targets in other indicators (e.g. zooplankton biomass).

WGECO then suggest caution when using "fish" dominated approaches, or approaches that assume foodwebs based on "adult only" diets.

1.2 Nik Probst

Why did WKFooWI simplify the evaluation criteria previously used by WGBIODIV? However the simplification appeared appropriate. More descriptions of the indicators would have been beneficial. The following work is required to make the indicators operational by 2018.

a) Specification of indicator metrics.
b) Gathering of relevant data.
c) Analysis of pressure–state relationship.
d) Development of indicator targets.
e) Constant updating and reassessment (also of targets).

Why were so many indicators scored highly for the criterion "management thresholds (targets) estimable". Why for indicators such as "biomass of trophic guilds" this criterion scored also highly. Was the thinking that healthy or good ecosystems consist of large, predatory fish (gadoids for the best) without scavengers and lower trophic groups. Whether this is ubiquitously the case, can be questioned. In fact, exploited systems may be modified, but also healthy and stable.

Also the assumption by WKFooWI that the best indicators are based on observed (empirical) rather than modelled data was supported.

1.3 Simon Jennings

The work of WKFooWI was much more focused than that of WGECO and will be easier to turn into advice. WKFooWI were clear that they were aiming for pragmatic approaches to identify, use and continue to develop FooWI. The analysis was complete to the extent possible. The shortlist of indicators provide a suitable focus going forward, provided ICES can move quickly towards developing the technical specifications for these general classes of indicator.

WGECO commented that several of the short-list of indicators proposed by WKFooWI are surveillance indicators. Given there is no technical description of the indicators this is a reasonable analysis based on current understanding of pressure–state links, but further selection and technical development of these indicators could tailor them to respond to impacts we can actually manage.

The focus on the development of a roadmap was limited (question c) and plans for moving towards future specification and implementation of D4 indicators are not clear. The WKFooWI report does define a process for selecting and developing D4 indicators and then applies it, and these are two important first steps in a longer process that might be described in a 'roadmap'. The advice could therefore show that two steps in a mapped process were complete, but would need to articulate the other steps, perhaps drawing on experience with D3, for which planning is more advanced than for the rest of the interrelated D1, D3, D4, D6 group. In the 'Roadmap' section of the WKFooWI report it is perhaps optimistic to brigade the short-list as suggested FooWI for current use, as I do not see evidence of technical underpinnings needed to use them right away in the MSFD context; although some have been the subject of research papers etc. and some components of these indicators are already available/ used in other contexts.

Possible steps for a roadmap that includes the steps already presented would be:

a) define criteria for selection of broad indicator classes (done WKFooWI and others);
b) make selection of priority broad indicator classes based on criteria and map to EC(2010) (done WKFooWI);
c) develop technical specification of indicators within the selected broad classes at Regional scales, taking account of contributions of existing indicators (D1, D4, D6) and available data;
d) screen refined indicators against criteria (strongly engaging RCS and representatives MS);
e) write up technical specifications of indicators that pass screening in clear accessible format, provide 'toolkit' for RSC and MS to generate and report indicators that pass screening.

With regards to the selected initial suite of indicators:

Guild level biomass (and production): If the initial aspiration is not to be comprehensive then significant initial progress will be made by drawing on data and indicators for other descriptors. This approach would also solve the challenge of identifying indicators that respond to management measures. For fishes, guilds could be based on the sum of biomass or production from groups of assessed stocks, especially when these cover a large proportion of biomass regionally. If large proportions of biomass in functionally important guilds are not covered at present in some regions then additional population assessments might be conducted to fulfil the aim of developing indicators for the guild (e.g. previous (2013) advice that assessments of all forage fish species that account for >5% of total fish biomass, or that are important in the diet of dependent species (especially when these are protected species)). These may support D3 as well. For higher predators (e.g. mammals and birds) estimates of abundance and production that would also fulfil the needs of D1 could be used and presented in aggregate form to support D4. Primary production from remote sensing already well supported by work of JRC, and this relates to the second of the short-list of indicators as well. However, the issue with moving away from species sensitive to the various types of mortality imposed by people (or the few cases where there is a well-established indirect response) will be that there is no identifiable management measure for MS to put in place. For this reason, and given criteria, I suggest the strength of pressure-state links may be used in the roadmap to help prioritize the work on guilds.

Primary production required to sustain a fishery: Since landings data are readily available at appropriate scales this indicator can be calculated with information on trophic level at size of the fished species, primary production and assumed transfer efficiency. No limits/ targets are clearly justifiable at the moment so far as I am aware, but the value of the indicator would respond to management if you wanted it to. Lots of likely controversy surrounding trophic level and transfer efficiency as assumptions here have a big effect on outcomes. However, cheap to calculate and applies to all regions.

Seabird (charismatic megafauna) productivity: Well developed and could also serve D1 and input to the guild analysis above.

Zooplankton size biomass index: If zooplankton assessment of some form were attempted this would also support the guild analysis above.

Integrated trophic indicators (mean TL, mean size): I assume this is where you assume LFI or a proxy is retained, maybe worth stating explicitly to link to the other ongoing and reported work. The two examples used in your title for this indicator are less understood and perform less effectively in most case studies the slope of size spectra, note also WGECO analysis in the reviewed section on large fish and trophic level (and concluded that the strength of connection was variable) so need to check consistency of message in material presented.

1.4 Benjamin Planque

The workshop report provides a clear answer to the request by the EU to ICES on the development of criteria and potentially useful indicators to address the relationships within the foodweb. Thus the objectives of the workshop, i.e. to produce a short list of foodweb indicators for the EU-MSFD and a defined process for selecting these indicators, were met. The methods used to evaluate the criteria were valid and conformed to acceptable norms. WKFooWI also accounted for its own internal bias.

WKFooWI choose to partition the indicators into three main groups 1) functional indicators linked to energy flows, 2) functional indicators linked to ecosystem resilience and 3) structural indicators linked to diversity and 'canary' species. This partition of the indicators was not so easy to follow and that several indicators could easily have been moved to another category. The preferred approach would be to consider:

- Foodwebs can be defined as networks in which nodes are trophospecies (which can be individual taxa, guilds, size-based groups of individuals, etc.) and connections between nodes are trophic flows (often expressed in mass, carbon or energy).
- A foodweb structure can often be described by its topology (i.e. the listing of trophospecies and trophic flows) eventually complemented by quantitative estimates of biomasses.
- The dynamics within the foodweb is best described by quantification of the trophic flows, how they vary over time and how they affect trophospecies biomass. In addition, reconfiguration of the foodweb topology may occur (by extinction or colonization).
- A pragmatic approach to the description of resilience in foodweb is provided in Levin and Lubchenco (2008) who identify three important qualities that confer resilience to networks: diversity, redundancy and modularity. This paper should have been referenced.

It is suggested to re- group the general categories and re-adopt the ones outlined above: structure, dynamics and resilience. This would not affect scoring and evaluation of individual indicators.

A primary focus is made on pressure-response and the establishment of rigorous thresholds for indicators. In many cases however, multiple synergistic pressures may prevent from establishing easy pressure-response relationships and associated thresholds. A balanced view between the use of indicators against thresholds and the use of trend-based assessment using indicators without threshold might be more appropriate.

The section on descriptions of the indices provides the rational for including individual indicators in the evaluation/selection process. However, this seems to have been written by many hands and the result is uneven. Some sections provide measurement/calculation methods, some provide guideline for interpretation, some provide indication of applicability for management, but few provide all of the above. A standardization of these sections would be helpful and useful.

There are two types of indicator missing from the list:

5) On the lower end of the pelagic foodweb lie unicellular organisms which can be autotrophs, heterotrophs or mixotrophs and belong to various taxonomic groups (e.g. bacteria, protozoans, diatoms, …). This part of the foodweb is believed to be particularly sensitive to warming and acidification of the ocean with responses that might likely percolates to higher trophic levels. These were not included as indicators changes in structure of dynamics in the lower part of foodwebs.

6) One of the simplest ways to describe a foodweb is a topological description (i.e. who eats whom). Surprisingly, no indicators of foodweb topology are presented.

Why did none of the five include an indicator for resilience?

2. LFI analysis carried out by WGECO

Overview of currently published regional LFIs and ongoing work

Area	LFI development stage	time-series	Specific treshold defined	Specific reference level
North Sea	Completed[1]	Yes	Yes	Yes
Celtic Sea	Completed[2]	Yes	Yes	Yes
Southern Bay of Biscay	Completed[3]	Yes	Yes	Yes
Central-Southern Tyrrhenian Sea	Ongoing[4]	Yes	No	No
Baltic Sea	Ongoing[5]	Yes	Yes	No
Poland EEZ	Completed[6]	Yes	Yes	Yes
Kattegat North	Ongoing[7]	Yes	No	No
Kattegat South	Ongoing[7]	Yes	No	No
The Sound	Ongoing[7]	Yes	No	No
Gulf of Cádiz	Ongoing[8]	No	No	No

2.1 Nik Probst

Nik reviewed Chapter 3 of the WGECO report.

2.2 Simon Jennings

The WGECO report contains extensive new work on the LFI and, when edited, this will therefore fulfil the DGENV request (question a). Since the ToR for WGECO was simply to continue working on LFI the work is necessarily not complete. I agree with most of the scientific conclusions but they are not strongly focused on application in the management system (if anything previous WGECO reports have been stronger in this regard). However, the work remains predominantly exploratory and descriptive, as it has for a number of years, and still has some way to go in terms of reaching maturity (agreed specifications and code for calculation that could be shared among MS and passed to other EG for example, good understanding of responses to alternate management actions).

WGECO did fulfil their ToR to extend the work to areas outside the North Sea. Although DGENV simply ask for ICES to continue working on the LFI, this work has been going on for several years now and I hope you can craft the advice to show clear direction in the new work being done and perhaps encourage more specific goal oriented requests that can then be passed to the relevant EG in future. My concern is that the group working on this topic are very good at continuing work, but also need to develop the work in a way that can be used by MS that may ultimately implement these methods (either inside or outside ICES fora).

2.3 Benjamin Planque

No comments with regards to the LFI work.