3 Ecosystem Indicators

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3.1 Introduction

Development and discussion of marine ecosystem indicators is currently a very active research topic worldwide. This is connected with the increased interest in moving forward with ecosystem-based management (EBM) of marine resources, and recognition of the need to index and summarise the state of marine ecosystems.

There are many types of indicators, including those of the physical environment (*e.g.*, climate), ecological, and socio-economic conditions. There is an entire professional journal devoted to the topic, called *Ecological Indicators*. Within marine systems, the most recent focus has been on developing indicators for ecosystem-based *fisheries* management (EBFM). Significant recent literature on this topic includes the symposium on "Quantitative ecosystem indicators for fisheries management" hosted in Paris in 2004 by the SCOR Working Group 119, of which a selection of papers were published in the *ICES Journal of Marine Science* (Vol. 62(3), May 2005; see the Introduction by Cury and Christensen (2005) and the afterward by Daan (2005)). Additional important reviews are by Degnbol and Jarre (2004), Fulton *et al.* (2004), Jennings (2005), and Link (2005). Important contributions focussed on the North Pacific are those by PICES (Jamieson and Zhang, 2005; Kruse *et al.,* 2006).

This section does not attempt an exhaustive and critical review of the 'state' of marine ecosystem indicators. Rather it provides a summary of the emerging consensus views on indicators of marine ecosystems, and makes recommendations applicable to North Pacific waters of PICES interest. In addition, this section attempts to take a broader view of indicators for EBM of marine systems rather than the narrower application to fisheries management (even though most of the research to date has focussed on this narrower application).

3.1.1 Classes of Indicators

The desire to develop indicators for EBM is rooted in the need to reduce the complexity of natural systems to an ideally small set of synthetic indices of ecosystem state, and to measure the progress of management towards the policy objectives for that ecosystem. In human health, an analogy for indices of ecosystem state might be body temperature and heart (pulse) rate which allow a rapid assessment of the immediate condition but without any indication of cause.

The PICES report on ecosystem indicators for the North Pacific (Kruse *et al.,* 2006, pp. 95–96) recognised a distinction between 'contextual' and 'management' indicators. Contextual, or 'audit', indicators provide information on the background conditions, which may include conditions over which humans have no control. Indicators of atmospheric and oceanographic climate such as temperature, salinity, sea ice, plus synthetic indicators such as the Southern Oscillation and Pacific Decadal Oscillation indices, are examples of contextual indicators. These have also been called 'descriptive' indicators by Degnbol and Jarre (2004). Management, or 'control', indicators summarise information on conditions over which humans have (some) direct control, and conceptually should be applicable to measure the results of management actions. Degnbol and Jarre (2004) call these 'performance' indicators which compare actual conditions with some desired set of conditions, such as a management goal. Degnbol and Jarre (2004) identify two additional classes of indicators which address mostly socio-economic conditions. These are 'efficiency' indicators, which relate environmental pressures to human activities, and which these authors suggest are highly relevant for policy-making. They provide an example of the volume of fuel per ton of fish caught as an indicator of energy efficiency. Vessel subsidies per revenue from fishing may be another example. The other class of indicators are 'total welfare' indicators which provide some measure of overall sustainability (which includes human social systems).

All these classes of indicators, with the exception of the contextual or descriptive indicators, are most useful (perhaps most meaningful) when applied in the context of specific objectives – *i.e.*, they indicate what the current conditions of the system are in relation to some desired state or condition. In this sense, indicators are best developed and applied within the broad concept of EBM, which should start with explicit statements of the objectives for management (*e.g.*, O'Boyle and Jamieson, 2006).

A framework that has gained broad acceptance in other fora, and which is beginning to be explored for marine systems, is the Driver-Pressure-State-Impact-Response (DPSIR) concept originally developed by the Organisation for Economic Co-operation and Development (OECD; *e.g.*, Smeet and Weterings, 1999; Rapport and Singh, 2006). In this framework Driving forces, such as climate change or human population growth, exert Pressures on the environment (*e.g.*, fishing effort) which change the State of the environment with possible Impacts to the functioning of the system. Societies may then provide a Response to these changes by modifying the Pressures (Degnbol and Jarre, 2004). Each of the levels in this DPSIR framework, with the possible exception of the Response (which is a policy action), use indicators to summarise their condition. Jennings (2005, p. 212) noted that "In a management framework supported by pressure, state, and response indicators, the relationship between the value of an indicator and a target or limit reference point… provides guidance on the management action to take". There needs to be a close relationship between indicators and clear policy objectives.

3.1.2 Characteristics of Good Indicators

Degnbol and Jarre (2004) and Rice and Rochet (2005) provide criteria for desirable indicators. Although directed towards EBFM, these criteria are sufficiently general to apply to ecosystem-based marine management more broadly. General principles are that the indicator should be sensitive (to the process being indexed), observable, acceptable, and related to the management objectives (Table 3.1.1). The best indicators would be those which are easily measured, cost effective, and easily understood (interpreted). In addition, Rice and Rochet (2005) provide a step-wise process for selecting the suite of ecosystem indicators:

Step 1 determine user needs,
Step 2 develop a list of candidate indicators,
Step 3 determine screening criteria,
Step 4 score candidate indicators against the screening criteria,
Step 5 summarise the scoring results,
Step 6 decide how many indicators are needed,
Step 7 make the final selection,
Step 8 report on the chosen suite of indicators.

However, as noted by Rochet and Rice (2005), the process of selection is not without difficulties. Experts may provide very different scores and these differences must be confronted through discussion in order to reach compromise on a final suite of indicators. One possibility is that test sets (data collected under known conditions) or simulations (*e.g.*, Fulton *et al.*, 2005) are used to challenge the indicators and verify their performance under a range of conditions. This can clarify the usefulness of candidate indicators.

3.1.3 Potential Indicators

In regard to the feasibility of developing indicators to assist with the management of marine resources, the 2004 Paris symposium allowed several conclusions to be drawn (Cury and Christensen, 2005):

- defining and implementing indicators is achievable with present knowledge, data, and frameworks;
- no single indicator describes all aspects of ecosystem dynamics; a suite of indicators is needed (covering different data, groups, and processes);
- environmental and low trophic-level indicators capture environmental change and bottom-up effects,
  - global effects of environmental change (*e.g.*, regime shifts) on higher trophic levels are not well captured by most indicators (at least individually, suites can elucidate these impacts);
- high trophic-level indicators (*e.g.*, birds, marine mammals) summarise changes in fish communities,
  - top-down effects can be quantified using trophodynamic indicators;

- size-based indicators are promising for characterizing fish community dynamics in a context of over-exploitation;
- ecosystem-based indicators are conservative,
  - they only show if the ecosystem is strongly affected, so trends and rapid changes must be evaluated by research and/or management;
- interpretation of indicators requires scientific expertise because of potential error and bias in their analysis;
- some indicators are better used for surveillance than for prediction. Regime shifts illustrate a situation where surveillance indicators may be useful;
- in an ecosystem approach to fisheries management, the objective is not to find the best indicator but rather a relevant suite of indicators with known properties;
- a strong feedback between scientific expertise and management is necessary to improve indicators and their practical use.

In terms of applications to *fisheries* management, a consensus is emerging on a core set of ecosystem indicators (*e.g.*, Degnbol and Jarre, 2004; Fulton *et al.*, 2004; Fulton *et al.*, 2005; Shin *et al.*, 2010). Ideally, this set should use species with fast turnover rates (to provide the potential for early warnings), species which are directly impacted (*e.g.*, by fishing, such as target species), species which are habitat-defining, and should include species at top trophic levels as these integrate and may be sensitive to a number of changes in their environments. Pelagic species that are highly variable (*e.g.*, in abundance) and which may track short-term environmental variability closely, may provide early warnings of changes but will have high noise-to-signal problems, *i.e.*, they may not indicate emerging trends well. Demersal and/or longer-lived species which dampen short-term variability may be better indicators of significant changes in system states. The emerging consensus list of core indicators (Table 3.1.2) includes the relative biomass of several groups of species; the biomass

Table 3.1.1 Desirable properties of indicators for marine ecosystem-based management (after Rice and Rochet, 2005).

Criteria	Sub-criteria
Concreteness	• Concrete property, or abstract concept? • Measureable units, or relative scale? • Directly observable, or output of models?
Theoretical basis	• Basis credible, or debated? • If derived from empirical observations, are the concepts consistent with established theory?
Public awareness	• Does it have high public awareness already? • Is its meaning readily understood? • Already enshrined in legislation somewhere?
Cost	• Uses measurement tools that are widely available and low cost?
Measurement	• Can variance and bias be estimated? Is it high or low? • Are the accuracy and precision of data collection methods known? • Is it subject to vagaries of different sampling gears? • Is it highly variable seasonally? Geographically? • Does it have high taxonomic specificity?
Availability of historical data	• Are historical data available? From how large an area? • Are the uncertainties of these historical data known? • Are these historical data freely available?
Sensitivity	• Does the indicator respond smoothly, monotonically, and with high slope?
Responsiveness	• Does the indicator respond rapidly (*e.g.*, within 1–3 years) of changes, or on longer (*e.g.*, decadal) scales?
Specificity	• How specific is the indicator to the processes being indexed?

ratios among these various groups; the extent of habitat defining epifauna and macrophytes; synthetic properties such as size spectra and diversity; various properties from the fisheries such as total removals, maximum length, size-at-maturity; and biophysical features such as temperature, chlorophyll *a* concentrations, nutrients, and contaminants. Note this list includes both contextual (descriptive) and management (control) indicators. The latter class of indicators, such as those from fishing activities, need to be related to the objectives (via target and limit reference points, directions, *etc.*; Fulton *et al.*, 2004; Link, 2005) in order to identify the management actions that must be taken to achieve that objective. The contextual indicators provide the background for these actions, and *may* suggest how the system might be changing. Many of these indicators are derived from fishery-independent surveys and several, in particular among the contextual indicators, are best interpreted as part of a time series. Both of these points suggest that a combination of fisheries-dependent and fisheries-independent information is required, which may not be available for all systems. The extent to which data are available in each of the PICES member countries to develop these sets of indicators is shown in Table 3.1.3.

Moving beyond the issue of fishing to embrace ecosystem-based marine management will require developing a broader set of objectives, and their associated indicators, to include other human uses and activities in marine systems. Examples are contaminants, marine transport, and coastal use issues such as aquaculture and development. These issues may be more appropriate for local- or regional-scale management plans although some, such as marine transport and non-indigenous invasive species, will have larger spatial scales similar to those for fishing. In addition, monitoring and indexing of atmospheric and ocean climate changes, and large-scale changes in ocean productivity, will also likely take a higher profile. The majority of these latter indices will be contextual, since humans are unlikely to have management control in the foreseeable future over climate variability. Much more work also needs to be done with developing indicators of these human uses and stresses on marine ecosystems, including socio-economic indicators that link to marine ecosystem status.

Table 3.1.2 Core set of consensus indicators for ecosystem-based fisheries management (from Fulton *et al.* 2004; Link, 2005).

1	Relative biomass	Example of gelatinous zooplankton, cephalopods, small pelagics, scavengers, demersals, piscivores, top predators
2	Biomass ratios	Piscivore:planktivore; pelagic:demersal; infauna:epifauna
3	Habitat-forming taxa	*e.g.*, proportional area covered by these epifauna and/or macrophytes
4	Size spectra	Slopes of community size spectra and their changes can be particularly strong indicators of community level changes
5	Taxonomic diversity (richness)	*e.g.*, based on species counts
6	Total fishery removals	Catch + discards + bycatch
7	Maximum (or mean) length	Maximum (or mean) length across all species in the catch
8	Size-at-maturity	Example of main target species, bycatch, and top predators
9	Trophic level or trophic spectrum of the catch	Average trophic level or spectra of the catch (*e.g.*, Gascuel *et al.* 2005) (may require that diet data be updated periodically)
10	Biophysical characteristics	*e.g.*, temperature, salinity, sea ice (where present), chlorophyll *a*, primary production, atmospheric indices (*e.g.*, PDO).

Table 3.1.3 Current data available among PICES member countries to calculate the Indicators in Table 3.1.2. Specific regions within countries are: Canada – Pacific North Coast Integrated Management Area; China – Yellow Sea; Japan – Kuroshio Current; Republic of Korea – Yellow Sea; Russia – Far-Eastern seas and adjacent Pacific Ocean waters; U.S. – Eastern Bering Sea.

		Have (at least) some of these Indicators been calculated regularly?						Are time series of data available to calculate more of these Indicators?					
		Canada	China	Japan	Korea	Russia	U.S.	Canada	China	Japan	Korea	Russia	U.S.
1	Relative biomass												
	- gelatinous zooplankton	–*	Y	–	Y	Y	Y	–	–	–	Y	Y	Y
	- cephalopods	–	Y	Y	Y	Y	–	–	–	Y	Y	Y	–
	- small pelagic fishes	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	- scavengers	–	–	–	some	Y	–	some	–	–	some	Y	Y
	- demersals	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y
	- piscivores	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y
	- top predators	Y	Y	Y	some	Y	Y	Y	Y	Y	some	Y	Y
2	Biomass ratios												
	- piscivore:planktivore	–	Y	Y	Y	some	–	Y	Y	Y	Y	Y	Y
	- pelagic:demersal	–	Y	Y	Y	–	–	Y	Y	Y	Y	Y	Y
	- infauna:epifauna	–	–	–	–	–	–	–	–	–	some	Y	–
3	Habitat-forming taxa												
	- nearshore	Y	some	some	some	Y	–	Y	–	some	some	Y	–
	- offshore	–	some	–	some	Y	Y	–	–	–	some	Y	Y
4	Size spectra	–	Y	–	Y	Y	Y	–	Y	–	Y	Y	Y
5	Taxonomic diversity	some	Y	some	Y	some	–	some	Y	some	Y	some	Y
6	Total fishery removals	Y	some	Y	some	Y	Y	Y	Y	Y	some	Y	Y
7	Maximum (or mean) length	–	Y	Y	Y	Y	–	Y	–	Y	Y	Y	Y
8	Size-at-maturity												
	- target species	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	some
	- bycatch	–	–	–	Y	Y	–	–	–	–	Y	Y	some
	- top predators	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	Trophic level or trophic spectrum of the catch	Y	Y	Y	Y	some	Y	Y	Y	Y	Y	Y	Y
10	Biophysical characteristics	some	Y	Y	Y	some	some	some	Y	Y	Y	some	some

* Dashed entries mean "No".

An example of developing indicators for this broader concept of EBM is the Ecosystems Considerations appendix prepared for the Bering Sea and Gulf of Alaska by the U.S. National Marine Fisheries Service (NMFS) to supplement their regional stock assessments (http://access.afsc.noaa.gov/reem/EcoWeb/index.cfm; see also Livingston *et al.,* 2005; Livingston, 2006). This report includes information on climate, fishing, and individual components such as nutrients and marine mammals. It also develops aggregate indicators of ecosystem production and composition from a variety of data sources. Ultimately, the report is planned to rely extensively on the indicators as well as outputs from ecosystem models; at present, however, these models remain in various stages of development and validation.

The report relies heavily on using multiple indicators to interpret ecosystem change and processes influencing change. For example, groundfish recruitment anomalies are evaluated relative to indicators of climate variability and harvest policies. Time trends in trophic level of the catch are weighed in evaluations of sources of change in groundfish production and size diversity. Broad-scale ecosystem management objectives have been expressed, such as maintaining pelagic forage availability to top trophic predators and maintaining diversity. However, more input is needed from policy-makers to define more specific ecosystem management objectives. Similarly, research is continuing to identify important ecosystem thresholds to define management actions. In the absence of such thresholds, a pilot effort to develop a more explicit ecosystem-based approach to management in the Aleutian Islands has incorporated indicators into a risk assessment framework as a tool for managers seeking to identify priority short- and long-term management activities (http://www.fakr.noaa.gov/npfmc/current_issues/ecosystem/AIFEP507.pdf).

As a caution, Kruse *et al.* (2006) note that most of the indicators mentioned above provide information on *current* conditions rather than predicting future states. Trends may be extended and forecasts provided for those indicators for which (sufficiently long) time series are available, but this assumes that future conditions (and indicator performance) will remain similar to past indicator performance. This may not be true under progressive climate change or significant regime shifts in which, for example, a lack of significant sea ice in the Bering Sea may make this indicator useless for that region. Similarly, not all indicators will be appropriate for all PICES regions. Hopefully a core set of common indicators can be developed, but careful selection and research on their application to, and appropriateness for, each region will be necessary.

The core set of indicators in Table 3.1.2 could be a starting point of discussion for information to incorporate into future PICES North Pacific Ecosystem Status Reports. In order for the indicators to be placed into a management context for a region, the main drivers of change will need to be identified since these may vary across regions. These drivers will identify what pressure measurements (*e.g.*, bottom trawling effort, catch removals, nutrient inputs, *etc.*) need to be included in addition to the ones already in Table 3.1.2.

3.1.4 Communicating Indicators

Developing indicators to assist with marine EBM will be pointless if the meaning of these indicators is not understood. Developing appropriate methods to communicate the results and interpretation of indicators to other scientists, marine managers, policy-makers, and the public is a central task of developing these indicators (*e.g.*, see the earlier section on “Characteristics of Good Indicators”). Kruse *et al.* (2006, p. 101) provide a group report with some thoughts on these issues, and the U.S. NMFS Ecosystems Considerations appendix explores different methods. A ‘traffic light’ approach (*e.g.*, Caddy, 2002; Choi *et al.,* 2005) provides a method to quickly tabulate a large number of indices and illustrate how they are changing in time, but it also removes what might be important nuances and details. Central considerations for communicating indicators must be to determine the intended audience, recognise whether the indicators are contextual (and therefore, mostly for information) or management (and therefore, potentially requiring a management action), and the extent of confidence in the indicator – *i.e.*, how certain are the input data and how good is the relationship between the indicator and the process it is indexing? Ultimately, it is important to recognise the subjective nature of this communication process, and not to expect any indicator to be simply a re-statement of data.

3.1.5 Recommendations

1. PICES should explore the use of the consensus suite of indicators (Table 3.1.2) in each of its regions to develop a common set of indicators to be included in each iteration of the PICES North Pacific Ecosystem Status Report;
2. PICES should use the WG 19 Ocean Management Activity reports and Fishery Science Committee (FIS) and Marine Environmental Quality Committee (MEQ) inputs to help identify region-specific drivers of change and pressure measurements in order to interpret status indicators in Table 3.1.2;
3. PICES should establish collaborations with social scientists to develop socio-economic indicators which include the effects marine EBM, such as cost-profit and employment in fishing activities. The ultimate goals should be to develop indicators which describe the coupled marine social-ecological system.
4. PICES should recommend a research activity to explore the use of additional indicators for marine EBM in each of its regions, building from those outlined here and in the U.S. Ecosystem Considerations appendix.

3.1.6 References

Caddy, J.F. 2002. Limit reference points, traffic lights, and holistic approaches to fisheries management with minimal stock assessment input. *Fish. Res.* **56**: 133–13.7

Choi, J.S., Frank, K.T., Petrie, B.D. and Leggett, W.C. 2005. Integrated Assessment of a large marine ecosystem: a case study of the devolution of the Eastern Scotian Shelf, Canada. *Oceanogr. Mar. Biol. Ann. Rev.* **43**: 47–67.

Cury, P.M. and Christensen, V. 2005. Quantitative ecosystem indicators for fisheries management. Introduction. *ICES J. Mar. Sci.* **62**: 307–310.

Daan, N. 2005. An afterthought: ecosystem metrics and pressure indicators. *ICES J. Mar. Sci.* **62**: 612–613.

Degnbol, P. and Jarre, A. 2004. Review of indicators in fisheries management – a development perspective. *Afri. J. Mar. Sci*. **26**: 303–326.

Fulton, E.A., Smith, A.D.M. and Punt, A.E. 2004. Ecological indicators of the ecosystem effects of fishing: final report No. R99/1546, Australian Fisheries Management Authority, Canberra.

Fulton, E.A., Smith, A.D.M. and Punt, A. 2005. Which ecological indicators can robustly detect effects of fishing. *ICES J. Mar. Sci.* **62**: 540–551.

Gascuel, D., Bozec, Y.-M., Chassot, E., Colomb, A. and Laurans, M. 2005. The trophic spectrum: theory and application as an ecosystem indicator. *ICES J. Mar. Sci.* **62**: 443–452.

Jamieson, G. and Zhang, C.I. (Eds.) 2005. Report of the study group on ecosystem-based management science and its application to the North Pacific. PICES Scientific Report No. 29, 77 pp.

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. *Fish and Fisheries* **6**: 212–232.

Kruse, G.H., Livingston, P., Overland, J.E., McKinnell, S. and Perry, R.I. (Eds.) 2006. Report of the PICES/NPRB workshop on integration of ecological indicators of the North Pacific with emphasis on the Bering Sea. PICES Scientific Report No. 33, 109 pp.

Link, J.S. 2005. Translating ecosystem indicators into decision criteria. *ICES J. Mar. Sci.* **62**: 569–576.

Livingston, P. 2006. Structure and purpose of the Alaskan *Ecosystem Considerations* appendix, p. 51 in Report of the PICES/NPRB workshop on integration of ecological indicators of the North Pacific with emphasis on the Bering Sea. PICES Scientific Report No. 33 *edited by* G.H. Kruse, P. Livingston, J.E. Overland, S. McKinnell, and R.I. Perry.

Livingston, P.A., Aydin, K., Boldt, J., Ianelli, J. and Jurado-Molina, J. 2005. A framework for ecosystem impacts assessment using an indicator approach. *ICES J. Mar. Sci.* **62**: 592–597.

O'Boyle, R.N. and Jamieson, G. 2006. Observations on the implementation of ecosystem-based management experiences on Canada's east and west coasts. *Fish. Res*. **79**: 1–12.

Rapport, D.J. and Singh, A. 2006. An EcoHealth-based framework for State of the Environment reporting. *Ecol. Indicators* **6**: 409–428.

Rice, J.C. and Rochet, M.-J. 2005. A framework for selecting a suite of indicators for fisheries management. *ICES J. Mar. Sci.* **62**: 516–527.

Rochet, M.-J. and Rice, J.C. 2005. Do explicit criteria help in selecting indicators for ecosystem-based fisheries management. *ICES J. Mar. Sci.* **62**: 528–539.

Shin, Y-J., Bundy, A., Shannon, L.J., Simier, M., Coll, M. , Fulton, E.A., Link, J.S., Jouffre, D., Ojaveer, H., Mackinson, S., Heymans, J.J. and Raid, T. 2010. Can simple be useful and reliable? Using ecological indicators to represent and compare the states of marine ecosystems. *ICES J. Mar. Sci.* **67**: 717–731, doi:10.1093/icesjms/fsp287.

Smeet, E. and Weterings, R. 1999. Environmental indicators: typology and overview. European Environment Agency, Tech. Rep. **25**, Copenhagen, 19 pp.