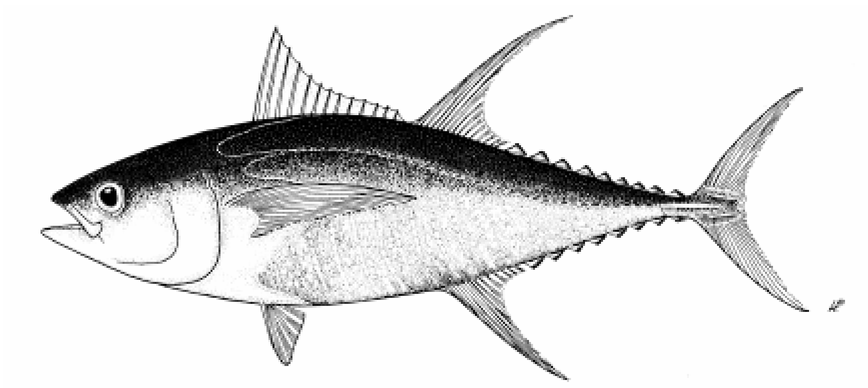
WCPFC–SC1 **EB WP–5**

Western and Central Pacific Fisheries Commission

1st Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission
WCPFC–SC1
Noumea, New Caledonia
8–19 August 2005

Potential ecosystem indicators for the WCPO



D. Kirby, V. Allain & B. Molony

Oceanic Fisheries Programme, Secretariat of the Pacific Community,
Noumea, New Caledonia

August 2005

Potential Ecosystem Indicators for the Western and Central Pacific Ocean

David S. Kirby, Valerie Allain, Brett Molony

Oceanic Fisheries Programme
Secretariat of the Pacific Community
BPD5, 98848 Noumea, New Caledonia

davidk@spc.int

Abstract

1) Ecosystem indicators are a way of reducing ecosystem complexity into a form that is most informative and useful to management. As a means of turning data into information, indicators are ultimately a communication tool facilitating science-based governance, i.e. the sustainable use of WCPO tuna resources and the conservation of associated species.

2) One framework suggested for the development of quantitative ecosystem indicators is PSR: *Pressure-State-Response*. This approach attempts to identify key forcing variables (e.g. oceanographic indices, fishing mortality), measures of system state, for the ecosystem and for individual components (e.g. stock status for target species) and indicators of system response to the pressures identified and to management action.

3) Appropriate methodologies for the derivation of indicators include univariate, bivariate and multivariate data analysis. These allow the investigation of single properties, the comparison of two or more properties (usually to investigate cause and effect), and the derivation of single indicators describing multiple series collectively representing the ecosystem as a whole.

4) In developing ecosystem indicators we must bear in mind the divisions of responsibility between ecosystem science and resource management. Scientists can suggest what analyses are feasible and sensible to do while resource managers must determine what scientific information they want, alongside other information concerning stakeholder priorities, how to reconcile different interests and decide on appropriate action. This is particularly so under an ecosystem approach to fisheries management, which requires value judgements based on economic, ecological and social trade-offs.

5) In conclusion, indicators will be important to identify ecosystem fluctuations affecting fisheries performance (e.g. potential changes in yields) and ecological impacts of fishing. The development of ecosystem indicators should allow all stakeholders (managers, investors, fishers, conservationists and other communities) to identify and better understand natural and fishery induced changes in marine ecosystems.

Introduction

Amidst a growing recognition that environmental variability and ecosystem effects of fishing should be 'taken into account' in an ecosystem approach to fisheries management, there is a need to characterise and develop objective measures for ecosystem properties.

An indicator is a metric describing the state or dynamics of the system of interest. Indicators can be presented as absolute values, particularly where the units are physically meaningful, or as anomalies, ratios or percentages. Indicators can also have a synthetic dimension, combining more than one variable into a composite index.

The use of indicators to monitor system state or dynamics is implicit in many traditional fisheries, oceanographic and ecological analyses (e.g. temperature, windspeed, sea-level pressure, catch, effort, abundance, distribution, biomass, diversity, etc.). What is new is the task of explicitly identifying or developing ecosystem indicators to be incorporated into fisheries management as a means to inform and/or evaluate decisions.

The main role of indicators is to characterise variability in terms that can then serve as a communication tool to relay information from scientific to management contexts, i.e. to reduce the complexity of an ecosystem into information that is easily comprehensible and compatible with the temporal constraints (both operational and strategic) of management.

A starting point in the development of candidate indicators is to ensure that they are quite specific to each potential pressure, state and response (see next section for discussion of these terms). Other qualities of a good indicator are that they:

- involve relevant stakeholders in their formulation and use, and are;
- founded on a rigorous scientific basis;
- easily measurable at reasonable cost;
- sufficiently well defined as to capture the main properties of the ecosystem;
- explicitly formulated at a particular scale and adapted with caution to other scales.

Ultimately, any ecosystem indicator must have the confidence of scientists and stakeholders in that it is objectively derived and is then useful for a particular purpose. Rice and Rochet (2005) propose an 8-step framework for choosing and using indicators:

1. Identify the users, their needs and objectives
2. Translate their objectives into candidate indicators
3. Assign weights to the following nine screening criteria of three types:
    - Interpretation (*concreteness*, *public awareness*, *theoretical basis*)
    - Implementation (*availability of historic data*, *cost*, *measurability*)
    - Application (*sensitivity*, *specificity*, *responsiveness*)
4. Score indicators on the criteria
5. Summarise results of the scoring
6. Decide how many objectives are required
7. Select the suite of indicators
8. Report on status using the indicators

Spatial considerations are important, especially for highly migratory species in a dynamic ocean environment (c.f. Sibert 2005). Legal processes and institutions (such as the Commission) necessarily superimpose political boundaries upon ecological boundaries. Scientific research must therefore be carried out with respect to both types of boundary, as well as with respect to the spatio-temporal patterns of the fisheries, as the boundaries chosen will to a large extent determine the results and information content of the analysis.

Pressure-State-Response

The *PSR: Pressure-State-Response* concept provides a useful framework for the analysis and development of ecosystem indicators. The two main pressures, or forcing factors, on exploited ecosystems are environmental variability and fishing. Indicators of *pressure* monitor these, indicators of *state* describe the ecosystem and its components, and indicators of *response* are changes in *state* that can be correctly attributed to *pressure*.

Pressure

Environmental indicators

These include measures of physical, chemical and biological properties such as can be monitored by oceanographic buoys and by satellite remote sensing. Variables such as sea-surface temperature (SST), sea-surface height (SSH), surface wind stress and ocean currents are important physical oceanographic properties; their large-scale distribution may be measured by satellite remote sensing or derived from numerical ocean models.

Most marine species have broadly defined temperature preferences and these can be used as an indicator of broad-scale distribution. SSH is another measure of the heat content of the ocean but has the advantage of being measureable through cloud. Surface geostrophic current anomalies, which relate to current shear and thus longline configuration, may also be derived from SSH data. Surface wind stress drives currents but also creates turbulence and may therefore be monitored as an index of larval feeding success and survival (cf. Cury and Roy 1989: optimal environmental window hypothesis; MacKenzie et al. 1994: Evidence for a dome-shaped relationship between turbulence and larval fish ingestion rate). It is possible to derive chlorophyll concentration, a measure of phytoplankton abundance, using satellite-based ocean colour sensors. Phytoplankton is a good indicator of environmental variability, integrating vertical and horizontal forcing (i.e. upwelling and advection) and can be used to delineate water masses and features where SST gradients are small. It may also indicate biological production at upper trophic levels, though fine-scale spatial correlation is not expected (Abraham 1998).

Polovina and Howell (2005) discuss the use of environmental indicators derived from satellite data. To use environmental indicators as ecosystem indicators it is necessary to define the biogeography of the ecosystems using physical, chemical and biological oceanographic factors. However, as the environment varies these boundaries also vary. Spatial indicators may explicitly measure these aspects, e.g. area of the western Pacific warm pool. The derivation of any indicator should therefore always be with respect to a clearly defined area and the variability of an indicator developed for one area, along with any inferences drawn from it, must be treated with caution when applied elsewhere. The same is true of applying indicators developed at one scale to analyses at another scale; there may be different variability at different scales therefore different signal:noise ratios.

Fisheries indicators

The most obvious indicator of pressure due to fisheries is fishing effort, for which some measure of *nominal* effort is usually derived with ease (fishing days; number of hooks) but *effective* effort is more difficult to determine, as it can take into account targetting practices, the configuration of the gear and its deployment in appropriate habitat.

A fundamental difference between environmental and fisheries indicators is that while both should be informative, management action can only control fishing pressure.

State

Oceanic top predators such as tunas, sharks, sea birds and marine mammals integrate all the ecosystem variability that they experience and therefore their population size and distribution can be considered indicators of the state of the ecosystem. Catch-per-unit-effort (CPUE) is commonly used as an indicator of abundance, once standardised to take account of effective effort. Campbell (2004) discusses fisheries performance/state indicators and their integration into a ‘traffic-light’ summary for management. Many other biological reference points derived from fisheries indicators are routinely derived in stock assessments (see the report from the 2003 IATTC workshop on reference points).

Size is an important structuring factor for marine ecosystems. Size-based indicators are relatively easy to compile, as length is commonly measured in fisheries statistics (Hampton 2004), and there are numerous potential size-based indicators, e.g. length-at-age, mean/maximum length, size-at-maturity, slope/intercept of size spectra. However, size-based indicators may respond both to fishing and to environmental variability, as food availability and temperature affect growth rates. As a long-term indicator the utility of size-based metrics will be in strategic rather than operational management. Reference points may be difficult to establish but directions of change are a more realistic prospect.

Trophic interactions (i.e. predation, including fishing) can modify the dynamics of marine ecosystems, resulting in trophic cascades and ecosystem regime shifts. Trophic spectra seem promising as an indicator of ecosystem structure. Stable isotopes ratios (C, N) are a means to estimate trophic level and are used as indicators of ecological processes. Species diversity is a synthetic indicator that captures multi-dimensional information about species composition, in terms of the number of species and their relative abundance (Legendre and Legendre 1998). Predator diversity can be investigated from the species composition of catch data, with due regard to any variations in the fisheries themselves that might confound the results. There is also the potential to develop indicators for prey diversity based on the diet study of Allain (2005), considering the number of prey items by family or functional group; size spectrum of prey cf. that for predators; and mean trophic level of the diet. This work is comparable to previous studies (Grandperrin 1975: sampling 1959–1962; 1968; 1971–1974) although monitoring has not been continuous.

A single index is usually insufficient to describe climate and ecosystem state and there is no consensus on the suite of indicators necessary to define ecosystem state. It is likely that different working definitions will be adopted, depending on the availability of information and the prioritisation of ecosystem components. Ideally we would have the ability to compare the present state of the system with some pristine reference state. This is the basis of the related concepts of *ecosystem health* and *ecological integrity*.

Ecological integrity is easily understood (i.e. how different is our exploited ecosytem from one that is not exploited) yet is extremely difficult to measure due to the need for pristine reference states and some understanding of the natural variablity of the system. This is especially important if the reference state is historical and from a discrete point in time, with no monitoring between that time and the present. If the reference state is co-temporal but spatially discrete, understanding of natural spatial heterogeneity is required before meaningful comparisons concerning ecosystem impacts of fishing can be made.

Ecosystem health is not a concept with which most ecologists are comfortable. An ecosystem will continue to function, therefore (arguably) be healthy, whether or not it contains the species and provides the goods and services that humans value. Therefore, if the concept of ecosystem health is to be used it is best considered pragmatically, and workable definitions derived based on an appropriate suite of ecosystem indicators; in the context of the following section, ecosystem health can be seen as a multivariate indicator comprising those component indicators that stakeholders agree as being important.

Response

Response indicators are perhaps best defined simply as derivatives (i.e. rate of change, acceleration) of state indicators that can be directly attributed to one or more pressure indicator. The challenge is to distinguish between ecosystem effects due to fishing and those due to environmental variability as both pressures may elicit the same response by driving state indicators in the same direction. There is no golden rule for doing this but an ‘ecological detective’ approach should be followed (*sensu* Hilborn and Mangel 1998), working back from the observed effect to the most probable cause. Indicators that can track ecosystem responses to management actions will be particularly useful.

Data analysis methods for indicators

There are three different analytical approaches to the development of ecosystem indicators: univariate analysis, bivariate analysis and multivariate analysis. This section will briefly review these methods as they relate to the development of ecosystem indicators; for a thorough description of methods consult Legendre and Legendre (1998).

Univariate analysis

Univariate analysis focusses on each ecosystem component singularly. The properties of interest in a single time series may include the occurrence of positive/negative values (such as define El Niño / La Niña phases based on positive/negative values of the

Southern Oscialltion Index: SOI). Threshold values may be taken as reference points. The mean and variance in the data may be of interest, although a series can also be standardised to zero mean and unit variance to facilitate comparison with other indicators. Extreme values may be of interest, or the number of times that values peak above a threshold value. Any clear trend in the data may be instructive and this can be investigated by functional approximation, whereby an appropriate functional form is identified that best describes the variability observed. Calculating first and second derivatives along the series will be informative as to trends and changes in trends over time. Fourier analysis can be used to identify periodic signals, although signals of interest may be at wavelengths longer than the available data.

As with any data analysis we must try to identify what is the signal and what is ‘noise’. Noise comprises observation error derived from instrumentation and/or sampling errors, and process error, which is a real signal, just not one that is of interest in the analysis. Depending on the purpose of the exercise, one person’s signal is another person’s noise, and series may need to be high- or low-pass filtered prior to analysis. This is the process of removing all low- or high-frequency variability respectively, the former often simply accomplished by averaging across adjacent time/space steps and the latter by de-trending.

Bivariate analysis

To avoid misleading interpretations of observed trends when analysing single indicators, it is important to seek corroboration by considering the behaviour of additonal indicators. Bivariate analysis should be carried out to explore interrelationships among variables and to identify statistical relationships suggesting cause and effect (i.e. pressure, response). The ideal is for an easily observed indicator to have a significant correlation with another indicator that is more difficult to observe or which responds with some lag; observation of the former may then be used to predict timing and degree of response of the latter (e.g. correlation between SOI and recruitment 1 or 2 years later).

More complex forms of bivariate analysis include wavelet analysis, which is capable of detecting the frequencies as well as the time periods for which correlation is greatest.

Multivariate analysis

There are a huge number of potential indicators that we can develop and monitor. Multivariate indicators can integrate all relevant variables into a single measure of system state. They therefore have the potential to be very powerful communication tools. However, multivariate indicators can be difficult to interpret, especially in terms of cause and effect relationships, so the potential for misunderstanding is also great.

Multivariate analysis can be used to identify coherent variability among ecosystem components and to develop composite indicators depicting ecosystem variability in a single series. Singles series may be combined in a multivariate measure as described by Campbell (2004) for fisheries indicators and Kirby et al. (2004) using Fisher Information as an index of coherent variability in climate indices and tuna recruitment for the WCPO.

Principal components analysis (PCA) is a multivariate technique commonly used as a first step towards identifying broad associations among variables and modes of variability. Hare and Mantua (2000) used PCA to identify two periodic cycles in 101 data series and used these results as indicators of ecosystem regime shifts in the North Pacific.

Some multivariate techniques such as canonical analysis (CA) can be used to identify highly correlated variables with a group. This then allows the number of variables to be reduced in further analyses, which need only include those that have the strongest effects.

Multivariate axes are usually fitted in such a way that the most variation within the dataset is plotted along the first axis. The next axis is at 90 degrees to the first through the next most variable dimension of the data cloud. This continues until n-1 axes are fitted. Unlike univariate and bivariate analyses, axes in multivariate analyses are composed of parts of many variables (i.e. merged). In some analyses, such as CA, the influence of each variable along each axis can be formally assigned using standardised co-efficients. This type of analysis allows the influence of all variables to be compared along all axes, highlighting the variables with the largest effects within a multi-variate data set. CA alone provides great insight into the identification of major variables and thus indicators.

The most commonly used multivariate technique in ecology is multi-dimensional scaling (MDS). Similar to other techniques, MDS incorporates a wide range of variables and re-scales them in multivariate space, typically using an ecological distance measure (e.g. Bray-Curtis similarity index).

Multivariate techniques can be used to reduce the number of variables worth considering, either to a smaller number of physically meaningful variables or to a composite indicator (e.g. Fisher Information or amplitudes of the axis coefficients). Techniques such as multiple regression and generalised linear/additive modelling (GLMs: Langley 2004,; GAMs: Bigelow et al. 1999) can then be applied, incorporating the multiple pressures (e.g. SST; chlorophyll) leading to a single response (e.g. CPUE).

Indicators as metrics for management

The choice of ecosystem indicators depends primarily on the information required to fulfill fisheries management objectives. With reference to the Convention these are to:

Article 5(d), "assess the impacts of fishing, other human activities and environmental factors on target stocks, non-target species, and species belonging to the same ecosystem or dependent upon or associated with the target stock";

Article 5 (e), "adopt measures to minimize waste, discards, catch by lost or abandoned gear, pollution originating from fishing vessels, catch of non-target species, both fish and non-fish species…";

Article 5(f), "protect biodiversity in the marine environment".

Following the PSR framework outlined above, indicators should be developed for environmental and fishing pressures and the status of target stocks, risk assessment indicators developed for bycatch species (including species of special interest) and species complexes (functional groups) and diversity indices developed for the ecosystem.

Ecological Risk Assessment is a framework for assessing the risk posed to bycatch species in the absence of sufficent data for full stock assessments. Risk is assessed on the basis of what is known about life history characteristics and fishing mortality, explicitly taking into account the uncertainty itself. Biological factors (e.g. longevity, age/size at maturity, fecundity, etc.), ecological factors (e.g. abundance, range, habitat, etc.), fishery factors (e.g. relative occurrence in different fisheries, retention rates, value) and social factors (e.g. retention by artisanal fishers) can all be incorporated in a single framework applying arbitrary but pre-defined weightings for each factor (see Fletcher et al. 2005). By multiplying or summing the values in such an assessment a ranking of species based on risks results, thus enabling prioritisation of research effort and management action.

Reference points are indicator values that are considered desirable (Target Reference Point) or undesirable (Limit Reference Point) and have been used in fisheries science and management for some time. Fisheries indicators are defined in terms of effort, biomass, yield etc., and then monitored as ratios of actual value to some target or limit reference point. This approach respects the division of responsibility between scientists providing information (deriving indicator values) and resource managers making decisions (setting reference points and control rules based upon them). However, whether it is appropriate or indeed feasible to construct reference points for ecosystem indicators is open to debate.

There are several key management questions on the development and use of indicators:

- How should the desirable direction for indicators to take be determined?
- How should (target and limit) reference points be established?
- How should management integrate both economic and ecosystem indicators?
- How should an indicator/reference point be connected to management actions?

Conclusions and recommendations

Ecosystem science is complex but as information is passed on to management, effective communication of knowledge and uncertainty becomes paramount, therefore this complexity must be reduced: ecosystem indicators serve this purpose.

Developing ecosystem indicators should allow all stakeholders to identify and better understand natural and fishery induced changes in marine ecosystems.

Indicators are rarely predictable, but a single indicator may have a functional form that gives ecologically plausible projections (e.g. wave forms) and bivariate and multivariate analysis may reveal lagged correlations between a pressure indicator and a response.

There is always a need for time series rather than point measurements; this leads to a requirement for continuous monitoring.

A risk assessment framework for the analysis of bycatch vulnerability could be developed using a range of ecosystem indicators

System-level indicators of ecosystem state should be developed to monitor stability, diversity and ‘ecosystem health’.

Given the complexity of ecosystems and their dynamic nature, management goals might be based around a desired level of variance in key indicators rather than absolute values.

Literature cited

Abraham ER (1998) The generation of plankton patchiness by turbulent stirring. *Nature* 391:577–580

Allain V (2005) Diet of large pelagic predators of the western and Central Pacific Ocean. Working Paper BI WP–2. 1st Meeting of the WCPFC Scientific Committee, Noumea, 8–19 August 2005

Bigelow KA, Boggs CH, He X (1999) Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. *Fisheries Oceanography* 8:178–198

Campbell R (2004) Performance indices, reference points and use of CUSUM plots for monitoring the performance of the longline fishery off eastern Australia. Working Paper MWG–1. 17th Meeting of the Standing Committee on Tuna and Billfish, Majuro, 9–18 August 2004

Cury P, Roy C (1989) Optimal environmental window and pelagic fish recruitment success in upwelling areas. Canadian Journal of Fisheries Aquat Sci 46:670–680

Fletcher WJ (2005) Application of qualitative risk assessment methodology to prioritise issues for fisheries management. ICES *Journal of Marine Research* (in press)

Grandperrin R (1975) Structures trophiques aboutissant aux thons de longue ligne dans le Pacifique Sud-Ouest tropical. Thèse d'état. Université d'Aix-Marseille II. 296 pp

Hampton WJ (2004) Tuna meta-population abundance and size structure as indicators of ecosystem impacts of fishing. Working Paper ECO–3. 17th Meeting of the Standing Committee on Tuna and Billfish, Majuro, 9–18 August 2004

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103–145

Hilborn R, Mangel M (1997) The Ecological Detective: confronting models with data. Monographs in Population Biology 28. Princeton University Press, 330 pp

Kirby DS, Lehodey P, Hampton J, Langley J, Allain V (2004) Regime Shifts in the WCPO and its tuna fisheries. Working Paper ECO–5. 17th Meeting of the Standing Committee on Tuna and Billfish, Majuro, 9–18 August 2004

Langley AD (2004) An examination of the influence of recent oceanographic conditions on the catch rate of albacore in the main domestic longline fisheries. Working Paper SA–4. 17th Meeting of the Standing Committee on Tuna and Billfish, Majuro, 9–18 August 2004

Legendre P, Legendre L (1998) Numerical ecology (2nd edn). Developments in Environmental Modelling 20. Elsevier, Amsterrdam, 853 pp

MacKenzie BR, Miller TJ, Cyr S, Leggett WC (1994) Evidence for a dome-shaped relationship between turbulence and larval fish ingestion rate. Limnol Oceanogr 39:1790–1799

Polovina JJ, Howell E (2005) Ecosystem indicators derived from satellite remotely sensed oceanographic data for the North Pacific. ICES J Mar Sci 62:319–327

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

Sibert J (2005) Ecosystem Boundaries and Indicators: Getting started with the ecosystem approach. Working Paper EB WP–6. 1st Meeting of the WCPFC Scientific Committee, Noumea, 8–19 August 2005