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Thematic catalogue of univariate indicators

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Report: Indicators for the assessment of thresholds and points of no-return. A report by Martina Austoni, Ana Cristina Cardoso, Genevieve Deviller, Lyudmila Kamburska, Dimitar Marinov, Francesca Somma and José-Manuel Zaldívar; Joint Research Centre, Institute for Environment and Sustainability, Ispra (VA), Italy

Executive Summary

This study gathers and classifies various published indicators of ecosystem function and diversity. The format of the document is designed to provide the best possible service for Thresholds project partners in selecting most suitable available indicator for their data. This document is conceptually linked to deliverable 5.1.1, which provides a database of selected literature sources from where the present indicators originate.

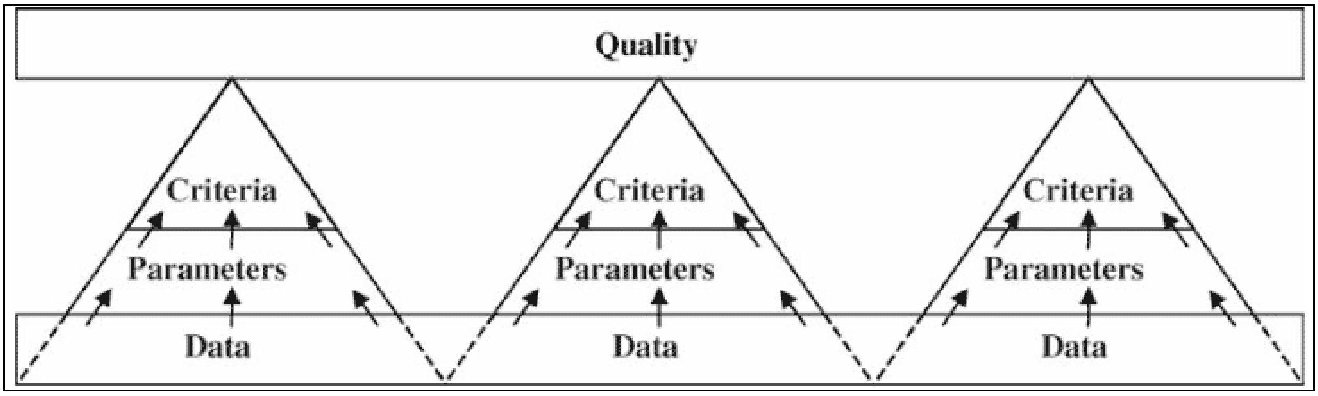
1. Introduction

The subject of ecological indicators is both complex and technical. Indicators are low signal/noise read-outs from systems reflecting deeply embedded processes. Informal, single factor indicators reflect superficial properties. Complex systems require formal, multifactor measures. Conceptual basis, importance and bandwidth of variables, reliability and statistical properties, data and skill requirements, data quality and archiving, robustness under technology change, and cost/benefit issues are factors in indicator design (Patten 2006). With ecological indication it is usually considered possible with a limited set of measurable parameters to make an assessment of an entity that is not directly measurable, e.g. (ecological) quality of nature.

Manu different levels of ecological indicators exist, making it a complex and potentially confusing concept. It is important to note that 'indicator' is a relative and nested concept (Turnhout et al. 2006). A criterion such as *diversity*, which can be assessed through an ecological indicator *species richness*, is in its turn an ecological indicator for ecological quality. Another example given by Turnhout et al (2006): PCB concentration in fat-tissue of a seal is an indicator for the health of seal population while the health of a seal population (in its turn) is one of the indicators of the ecological quality of the aquatory.

The construction of ecological indicators implies a process of selection, integration and aggregation. Nutrient availability PCB concentration in fat-tissue of seals are just two of the possible indicators for the ecological quality of a certain area. Different parameters are aggregated in the ecological indicator, which presents information of what is indicated (Fig. 1.1).

Figure 1.1 The spectrum of coverage of ecological indicators between data and quality. Source: Turnhout et al. (2006).



The scientific literature of the past decades provides a wealth of ecological indicators to describe the state, or change of state of natural environment. Some are classical indices, which have been more or less successfully used for over half a century. Others are new developments supported by recently available computer power and have not been extensively tested, if at all. Needless to say, a results oriented researcher can spend weeks or months of valuable research time reviewing the literature and searching for best solutions.

In this report we provide an overview of the most essential indices and indicators of ecosystem function and diversity, both, historic and more recent ones. The indices are categorized hierarchically under sub-themes to facilitate fast browsing and finding of best options.

The main sources of this catalogue are published peer-reviewed journal articles as well as a few major textbooks and monographs. A combination of key-words and expressions was used to search public, as well as proprietary databases (ASFA, ISI, Google). To facilitate the use, original literature references, where the indicator was first published, are provided. When available, also later references describing the successful use or characterisation of the indicator are added.

While compiling this catalogue, it soon become apparent that it will not be feasible, or even meaningful, to include all indices. The continuous flow of new literature, and the emergence of a new journal '*Ecological Indicators*' (Elsevier) adds new knowledge on a weekly and monthly basis. Thus a stringent selection has to be made, keeping in mind the goals of the Thresholds project (to develop the quantitative and predictive scientific tools to identify thresholds and points of no-return of environmental sustainability).

1.1. The lay out of the catalogue description

In the following we give a short narrative description of each category of the indices. The sequence of categories is linear and rather arbitrary, not truly reflecting the hierarchical nature of indices nor their mutual relations. Needless to say, there are many categorisations available and as we have no a priori reason so prefer one over the others, the selection used here is to a certain degree arbitrary. This document is accompanied by a more detailed description of indicators[1], where the categorisation follows the lay-out of Jørgensen (2005).

This document is accompanied by an Excel sheet, which contains a categorized list of indices, their acronyms (if available) and the unique record number which links the indicator to the original literature source(s) and/or papers demonstrating the application of the indicator in the EndNote database (part of D5.1.1). Originally each indicator was supplemented with an array of descriptors (like pressure, key ecosystem, key ecosystem characteristics, indicator purpose, environment, scale), but any of these descriptors was applicable to only a relatively small fraction of the indicators, resulting in a rather sparse table. Thus these columns were dropped as the empty cells were rather disturbing and did not provide the expected informative help.

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[1] Indicators for the assessment of thresholds and points of no-return. A report by Martina Austoni, Ana Cristina Cardoso, Genevieve Deviller, Lyudmila Kamburska, Dimitar Marinov, Francesca Somma and José-Manuel Zaldívar; Joint Research Centre, Institute for Environment and Sustainability, Ispra (VA), Italy

2. Description of the catalogue

To give a general classification of published indices and indicators is not a trivial task. We used our best intuitive approach to cluster the indices into related groups, providing a reasonable amount of descriptors (e.g. environment where it has been used, indicator purpose, scale, etc.) to help the user to select easily the most appropriate ones. Unfortunately, no descriptor is general enough to be applicable to all indices. Some indices stem out of economic sciences or combine social and environmental sciences. Others are information theory based, yet other are simple abundances of indicator species. Depending on the question asked, all can serve a useful purpose, even though a common nominator is difficult or impossible to define. Many related indices should actually be treated as a family of indices. E.g. the classical information theory related Simpson and Shannon entropy (Simpson 1949; Hurlbert 2001; Grunewald and Schubert 2006; Isák 2006).

2.1. Inherently univariate indices

This group uses inherently univariate indicators, which are usually very easy to measure and interpret. Sea surface temperature, secchi depth, concentration and percentage of dissolved oxygen, biological and chemical oxygen demand, bulk measurements of dissolved and particulate nutrients belong to this group. These are often included in routine monitoring programs and have long time series available.

Many univariate indices stem from the long tradition of fisheries oceanography. Commercial fish catches, abundance of individual taxa, population dynamics of commercially important stocks are examples of this category. An example of the utility of commercial stock estimates is the well described pattern of regime shifts in the Humboldt Current system, driven by frequent direct environmental perturbations of the El Niño Southern Oscillation, which controls the shifts between alternating anchovy and sardine dominated ecosystems (Alheit and Niquen 2004). This group also includes monitoring of selected sentinel organisms, e.g. Mussel Watch (O'Connor 1992).

Due to the commercial interest in fisheries dynamics, many of these indices have been thoroughly investigated and the statistical methodology is often elegant and well developed. E.g. arranging a univariate parameter into a two dimensional array (years in columns and monthly average in rows) allows a contour plot type representation of the data (e.g. Beaugrand et al. 2003). Concomitantly the same 2D matrix can be used in ordination analysis to scrutinize the information content and threshold type behaviour in time.

The pressures related to published univariate indices are often climatic (temperature change driven) and also anthropogenic (usually over-fishing). Eutrophication related pressures are only seldom reflected in fisheries related publications.

2.2. Complex indices

Complex indices are various arithmetic combinations (ratios, multiplications, etc) of simple univariate parameters. The number of univariate parameters involved varies, as does the weight given to each parameter. The main advantage of complex indices over inherently univariate ones is that they are believed to grasp the state of the ecosystem in it's entirety, concentrating the most important properties of the system into one number. Ideally the chosen attributes cover both, structural and functional indices at the community level. Obviously, the index components are related to the degree of sensitivity/tolerance to an environmental stress gradient (Pearson and Rosenberg 1978). Examples are the ecofunctional quality index (EQI), which incorporates primary productivity, structure and productivity of the benthic community, taxonomic diversity and trophic complexity (Fano et al. 2003), the TRIX index (Vollenweider et al. 1998) attempting to express the level of eutrophication in one number, Marine Biotix Index (Borja et al. 2000), which relies on the sensitivity of benthic macrofauna to pollution. The driving force behind complex indices is the need to devise a expression to make information comparable over a wide range of trophic situations and habitat types, to convey the essence of findings into a single number. Miller et al (2006; 2006) developed and demonstrate the use of plant-based Index of Biological Integrity (IBI) to evaluate headwater wetland condition in response to anthropogenic disturbances in the Ridge and Valley Physiographic Province of central Pennsylvania. To construct the IBI, they evaluated 50 attributes of the plant community, including species richness, diversity, and evenness. Disturbance was quantified for each site using information on surrounding land use, buffer characteristics, and an assessment of potential site stressors. Only a small fraction of the 50 tested plant attributes proved to be good metrics. Selected metrics were highly correlated to chosen disturbance gradient, displayed a consistent and predictable response, and were ecologically meaningful (Miller et al. 2006).

However, there are an almost infinite number of ways to calculate a compound index from even a few input indicators, which ultimately result in a high degree of subjectiveness and arbitrary agreements. Additionally, there are more than one way to transform the original data in the calculation formula. Trophic parameters (e.g. production rate, biomass, etc.) are generally non-normally distributed, but simple log transformation in generally sufficient to approach normality (Vollenweider et al. 1998). In other instances beta, gamma or Box & Cox transformations have been used (Vollenweider et al. 1998, and references therein). Often various authors have been tempted to 'slightly' modify already well established indices in order to 'better reflect the local conditions' or 'improve the indicative power' (Borja et al. 2000). Although no index should be treated as a dogma, custom-made modifications render the index as incomparable with it's original version. Nevertheless, many such indices have been successfully used and new ones, which are potentially promising to reveal thresholds in environmental gradients, are published frequently.

Andreasen et al (2001) have attempted to define some rigorous criteria for an ideal terrestrial index (Terrestrial Index of Ecosystem Integrity), which should encompass chemical, physical and biological integrity, reflect ecosystem health, biodiversity, stability, sustainability, naturalness, wildness and beauty. However, they realize that our lack of understanding of ecological systems limits how close we can get to expectations. They find that in a regulatory context, the index should be "bulletproof and defensible in court under cross-examination". The concept of an integrated index has been seriously criticized, remains controversial and we are far from consensus.

2.2.1. Marine benthic

Marine benthic indices generally rely on the paradigm of Pearson and Rosenberg (1978), stating that benthic communities respond to improvements in habitat quality in three progressive steps: the abundance increases; species diversity increases; and dominant species change from pollution-tolerant to pollution-sensitive species. Marine macrozoobenthic indices ascribe species to an ecological grouping, according to their sensitivity to an increasing stress gradient (Borja et al. 2000).

2.3. Entropy based indices

Although ecological indicators of all varieties are of scientific interest, biodiversity, as a synoptic measure, holds a special appeal to the public and is often addressed directly by policy (Ainsworth and Pitcher 2006). These indices are based on information theory and usually theoretically very well justified and interpreted. Many describe statically species (or higher taxon) diversity, thus ignoring changes in community structure not associated with the change of diversity. Several are known already for over 50 years (e.g. Shannon and Simpson diversity indices) (Shannon 1948; Isák 2006). This type of diversity indices can be calculated from individual organisms (numerical diversity, bits ind^{-1}) or biomass (biomass diversity, bits g^{-1}). Apart from the taxonomic diversity, Shannon index has also been applied to abundance data of major functional groups (e.g. grazers, scrapers, suspension-feeders, predators, etc., Gaston and Nasci 1988). An example is the Q-90 biodiversity index, a variant of Kempton’s Q index, which refers to biodiversity as organismal diversity at the level of species functional groups, and as an example has been used in the ECOSIM model (Ainsworth and Pitcher 2006).

The commonly used diversity indices are not void of shortages. Diversity varies in a nonlinear fashion with the size of the elementary sampling unit (quadrats, parcel of water, etc.) as well as with the extent of the study area (Chong and Stohlgren 2006). Even where the sampling effort had been equal across sites, species diversity is a questionable criterion when habitats with different productivity levels are compared, or when the number of rare species is large (Dufrene and Legendre 1997). As proposed by Cousins (1991), representativeness, or representative diversity would be a better criterion to evaluate comparative richness, or the effect of isolation and fragmentation. In monitoring programs designed to evaluate the impact of management practices, it will also be useful to weight the species abundances in a site in order to account more for the typical than the vagrant species (Dufrene and Legendre 1997).

Others information theory-based indices are new theoretical developments, attempting to incorporate also the functional traits and services of the ecosystem and referred to under a variety of different names in the literature (energy, exergy, eco-exergy, emergy index) (Cabezas et al. 2005; Ludovisi et al. 2005; Jørgensen 2006; Ludovisi 2006; Vassallo et al. 2006). Although promising (as they combine not only structural, but also functional diversity), these new indices have not yet been used widely and we lack even basic understanding on their practical performance. This situation is probably going to change soon; Austoni et al (2006) have used exergy of macrophytes to assess ecosystem health in coastal lagoons in accord with the Water Framework Directive of the European Union. Silow and In-Hye (2004) assess the health of the Lake Baikal ecosystem in an experimental approach using exergy in a readily understandable manner (even for a novice in math). Exergy is calculated as a function of the biomass multiplied by a weighting factor (β), which expresses the quantity of information embedded in the biomass. Only relatively few values of β are published until now, which hampers the use of exergy as an integrated indicator (Silow and In-Hye 2004; Austoni et al. 2006).

Fath et al. (2003; 2004) have used Fisher Information theory to come up with an index that is sensitive to transient behaviour in ecosystems, while distinguishing natural fluctuations from fundamental changes in system state. Fisher Information is a scale independent indicator of biodiversity, but may be an underestimation in communities in which spatial aggregation of individuals is strongly clustered (Schulte et al. 2005).

2.4. River indices

Rivers have often served as recipients of human wastes, raising the need to monitor their health downstream the pollution source and in time. This has led to a long and diverse tradition of well elaborated biotic indices. Often the indices are incorporated into governmental monitoring programs and specific to one region or a country. Many use specific indicator species, which naturally makes the index applicable at a relatively restricted region or context.

An important concept has been the integration time of the environmental signal (or pollution effect) by the organisms. Unicellular phytoplankton or benthic diatoms respond rapidly to fluctuations in the environment, while sessile benthic macrofauna integrates over several years. The rooted macro-vegetation, an increasingly popular class of indicator organisms (Ferreira et al. 2005), get their nutritional resources from the sediments and are thus less directly related to the nutrient content of the water. Eutrophication though, by promoting phytoplankton development, reduces the light availability to the submerged benthic macrovegetation.

2.4.1. Diatom flora

Various diatom indices provide a promising perspective to assess water quality properties (Kelly and Whitton 1995; Kelly and Whitton 1998; Prygiel 2002). As sessile organisms, diatoms respond directly to changes in the river water quality and can not change their habitat. Several European countries have developed national indicator systems to use benthic diatoms as water quality criteria (Van de Vijver and Beyens 1998; Kelly et al. 2001; Prygiel 2002). The European Union has adopted a standard method to use benthic diatoms in water quality assessment (Water quality – Guidance standard for the routine sampling and pre-treatment of benthic diatoms from rivers CEN/TC 230). The down-side of these indices is the need for highly qualified personnel for species identification.

2.4.2. Benthic macrofauna

A number of benthic macrofauna based indices have been developed for running waters (Armitage et al. 1983; Skriver et al. 2000). Macro-invertebrates are perhaps the most widely used organisms to reliably assess river water quality[2]. The indices utilize the relatively sedentary nature of macro-benthic animals, which prevents them from avoiding deteriorating water/sediment quality

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[2] E.g. the AQEM (www.aquem.de) and STAR projects (www.eu-star.at)

conditions, and also the long life span of the animals, allowing to integrate quality conditions in time. As with diatom indices, they require detailed taxonomic expertise (however, see Crains et al. 1968) and often a painstakingly detailed analysis of species. The indices have a relatively restricted spatial applicability. Countries with strong monitoring traditions have developed their own suitable indices, while in regions where such work has not been done, extrapolation of indices from neighbouring regions must be considered with care and perhaps, with necessary modifications.

In complement to the traditional macrofauna indices, new developments have linked faunal composition relatively directly to well established eutrophication parameters like total phosphorus and nitrate (Smith et al. 2006), which considerably eases interpretation.

2.4.3. Macrovegetation

Macrophytes embrace several taxonomic groups of organisms: macro-algae, liverworts and mosses, ferns, and flowering plants. Macrophytes are the prime structural element in the open water column of rivers and lakes. Numerous groups of organisms make use of the considerable enhancement of spatial diversity provided by the surface of the plant organs and the spaces in between. The life-form of macrophytes determines their sensitivity to water quality (Heino et al. 2005). Submerged floating leaf and surface living plants tend to be more prone to changes in water chemistry. Reeds and other helophytic species, although closely related to the aquatic environment, are rather to be dealt with under the element of hydro-morphology.

2.5. Indicator species based

The heart of these indices are carefully selected species, which are assumed to respond predictably to environmental changes (Ellenberg 1979; Fanelli et al. 2006).

Managers often use species indicator lists to assess effects on the environment. However, these indicators have rarely been scientifically tested. Cousins et al (2004) discuss if plant functional traits (PFTs) may be a key to select suitable indicator species for monitoring land-use change in Swedish rural landscape. They found no association between successional change and plant functional traits, but a response in plant functional traits was found along the wetness gradient. However, the more common ‘non-scientific’ indicator species responded fairly well to the varying gradient categories along both gradients (succession and wetness), justifying the need to validate the ecological mechanisms behind the present-day indictor species (Cousins 1991).

Dufrene and Legendre (1997) present a ‘simple’ method to find indicator species and species assemblages characterizing groups of sites. The method is based on ordination techniques.

Fleishman et al. (Fleishman et al. 2005; Fleishman et al. 2006) discuss and use indicator species to predict species richness. Values of species richness are used widely to establish conservation and management priorities. Because inventory data, money, and time are limited, use of surrogates such as “indicator” species to estimate species richness has become common. Identifying sets of indicator species that might reliably predict species richness, especially across taxonomic groups, remains a considerable challenge. The approach of Fleishman et al. is appropriate for both, indicator species and species richness (species diversity).

2.6. Physiological and biochemical indices

Physiological indices are usually expressed as ratios of physiological rates (Mayer et al. 2004). E.g. the ratio of primary production to community respiration indicates the degree of heterotrophy of the system.

Some physiological indices are very specialized but rather elegant, using modern techniques, often molecular. An example is presented by Johnstone et al (2006), where the authors evaluate the total antioxidant status in algal tissue extraction to assess the stress response of algae as a proxy to environmental impacts in urban aquatic habitats.

3. Conclusions

The range of biodiversity and ecosystem functioning is vast. Some have been in operation for decades, and can be considered as classical (e.g. Shannon diversity, several benthic macrofauna indices). However, in these days we see a rapid development in the indicator research field, reflected in the emergence of new concepts, new methods, new indices and increasing interwinding of natural sciences with economy and also social sciences. This quick development is facilitated by readily available computer power in these days, but also the needs of the society.

The rapid emergence of new concepts and indices makes a comprehensive categorisation difficult, if not impossible. The existing categorisation schemes more of less fail to encompass the diversity of newly emerged indicator concepts. This a degree of arbitrariness in the categories presented in this document was unavoidable.

We are still convinced that this document is an inspiring and useful reading for the Thresholds community, particularly when used in parallel with the twin deliverable D5.1.1. However, when more detailed descriptions of the indices or methods is needed, we strongly urge the reader to print out the original paper(s), which due to space and time constraints were only circumscribed in this document, and in D5.1.1.

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