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Ecological indicators for the pelagic zone of the ocean from remote sensing

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ABSTRACT

It is generally accepted that responsible stewardship of the ocean implies ecosystem-based management. A requirement then arises for ecosystem indicators that can be applied in serial fashion with a view to detection of ecosystem change in response to environmental perturbations such as climate change or overfishing. The status of ecological indicators for the pelagic ecosystem is reviewed. The desirable properties of such indicators are listed and it is pointed out that remote sensing (ocean colour, supplemented by sea-surface temperature) is an important aid to achieving them. Some ecological indicators that can be developed from remotely-sensed data on ocean colour are tabulated. They deal with the seasonal cycle of phytoplankton biomass, production and loss terms, annual production, new production, ratio of production to respiration, spatial variances in phytoplankton biomass and production, spatial distribution of phytoplankton functional types, delineation of ecological provinces and phytoplankton size structure.

1. Preamble

In the stewardship of the ocean, it is now generally accepted that procedures for management and continuing oversight should have an ecosystem basis (Garcia & Cochrane, 2005). In other words, it is understood that management ought not to be motivated by only one or a few narrow goals (which may in fact be mutually antagonistic), for example the yield or abundance of particular exploited fish stocks. Rather, it is believed that the ecological context should be considered in some holistic way, such that, in the example just mentioned, the integrity of the ecosystem in which the exploited fish stocks are embedded will not be jeopardised, as it might otherwise be, by concentrating attention on only a small part of the whole.

The mandate then is to think broadly and think ecologically. Given this point of departure, the next requirement is to identify characteristics of the ecosystem that capture the imperative to *quantify* its somewhat elusive properties such as health, vigour or resilience. In particular, we need to identify or develop ecosystem metrics that, if applied *in a serial manner*, would enable us to detect whether the ecosystem is modified in any significant way by, for example, the suite of processes we describe collectively as climate change or by heavy fishing. We refer to these desired metrics as ecological indicators. In this paper, we consider the use of remote sensing in the development and application of ecological indicators for the pelagic marine ecosystem.

2. Some existing indicators and their limitations

What measurable properties of the pelagic ecosystem have been suggested as potential ecological indicators? Rice (2003) has summarised the variety of ecological indicators that have been proposed or that are already in use, and has written at length on factors arising in their implementation. They number "in the hundreds". They can be organised into rather few classes.

Indicator species, of which an exotic example is the canary in the mine shaft, may reveal something about the environment, but necessarily cannot be expected to convey information on the entire ecosystem (Spellerberg, 1991). Similar limitations would apply to attributes of the population of a particular species (especially of valued, exploited populations), such as its size distribution. The connection between population structure of one species and the integrity of the ecosystem as a whole remains to be demonstrated. Indeed, such indices are merely extensions of an approach, already found wanting, based on dynamics of single populations. Because they are not properties of the ecosystem-at-large, they have only restricted value as ecological indicators.

Indicators based on the relative abundance of species in a community (evenness, richness, diversity) are numerous (Ludwig & Reynolds, 1988; Legendre & Legendre, 1998). Apart from technical limitations on interpretation, these methods have the disadvantage that implementation requires identification of species and enumeration of individuals. Generally, such activities are difficult, time-consuming and costly (Bundy et al., 2005). Ordination methods (Gauch, 1982; Legendre & Legendre, 1998) likewise suffer from difficulties in interpretation of results and are costly to implement, given that they also require identification and enumeration.

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Another class of indicators seeks to capture community properties without identification of species. An example is the community size spectrum, for which a body of theory already exists outside the subject of ecological indicators (Platt & Denman, 1977, 1978; Silvert & Platt, 1978, 1980). Implementation does not require the expertise to identify taxa. Sizing of the organisms can be done in part by automatic methods, but for some size intervals, individual sizing with the light microscope may still be necessary. Implementation is not trivial (Blanchard et al., 2005; Jennings & Dulvy, 2005; Stobberup et al., 2005). When the variables are suitably transformed, the spectrum can be linearised, the slope and intercept having ecological interpretations. For example, the intercept is an indirect measure of ecosystem productivity. But as Rice (2003) points out with justification, if the goal were to index ecosystem production, it would be more expedient to measure it directly than to infer it from a size spectrum.

A final class of indicators is based on quantitative attributes of the community as revealed by input of observations to a model or models of the marine ecosystem. For example, a compartmental model of the pelagic food web could be used to infer ecological fluxes between compartments from measurements of the biomasses in the compartments according to the inverse method (Vézina & Platt, 1988). Any set of fluxes, or the aggregate of fluxes, may be used as ecological indicators (Moloney et al., 2005). In another approach, mass-balance criteria are used to infer particular ecological fluxes that may otherwise be exceedingly difficult to measure (Christensen & Pauly, 1992; Christensen & Walters, 2004). These approaches have two major limitations. First, the results will depend on the structure (food-web topology) of the ecosystem model in use (Cury et al., 2005). As an example, a model that failed to include a microbial loop would yield a quite different mass balance, and a different set of fluxes, than one in which a microbial loop were included. Because the same set of observations can be made to yield different conclusions depending on the underlying model, the results may be contentious, and inaccessible to those not expert in ecosystem modelling. The second difficulty is that implementation requires enormous effort of sampling, analysis and interpretation just to make a single realisation of the model. It may be prohibitively expensive to repeat them.

Given that the rationale for development of ecological indicators is to detect temporal modifications in the structure and function of the ecosystem occurring under perturbations, either natural or anthropogenic, it follows that the indicators should be computed at intervals so that possible differences may be revealed. The requirement for serial measurements raises another issue, that of resource requirement. As we have seen, many of the candidate indicators are exceedingly difficult, and costly, to measure. Hence the frequency in time at which they could be measured may be compromised by the cumulative cost of repeated measurement. If indicators are too expensive to implement sufficiently often to document change, and in a timely enough manner to be useful, they have little merit as operational metrics.

Similarly, the spatial representativeness of observations may also be compromised by the costs involved in making the measurement. Fixed-point measurements from ships offer no peripheral vision. If only one location is used for all the sampling, it will be a difficult problem to know the spatial extent that this station can be taken to represent. And if it is indeed representative of a particular ecological province (*sensu* Platt & Sathyendranath, 1988, 1999; Longhurst, 1998), it will be impossible to know how the resultant indicators are influenced by conditions in neighbouring provinces (the oceanographic context).

3. Desirable properties of ecological indicators: potential role of remote sensing

In view of the difficulties surrounding the development and routine application of ecological indicators as conceived at present, it is worthwhile to consider what properties ideal indicators might have. They should represent some well-understood and widely-accepted ecosystem property that can be quantified unambiguously in standard units. They should be measurable rapidly, at low cost, with a repeat frequency compatible with the intrinsic time scale implied in the measurement and also with the time scale relevant to the applications envisaged. Ideally, the same indicator would be suitable for a variety of applications, implying that indicators of choice would be measurable at a variety of scales. They should be capable of implementation in many locations using the same objective methodology, to allow comparisons between ecosystems.

These are stringent conditions indeed, and it would be impossible to meet them using conventional sampling platforms. However, they are not difficult to meet using remote sensing, provided a suitable metric can be defined. Remote sensing has the potential to provide data with high spatial resolution (1 km or less) at high repeat frequency (1 day). In developing indices from remotely-sensed imagery, all spatial structure can be preserved (data, and indicators derived therefrom are georeferenced). Methods that fail to document and conserve spatial structure will be intrinsically inferior to those that do not. At the same time, the possibility always remains of taking averages, weighted or unweighted, over any spatial domain of interest. Potentially, coverage is global, so that any degree of spatial aggregation is possible: the oceanographic context can be shown for any chosen region. Of course, data collected by ships provide a valuable and complementary means to enhance the information collected by remote sensing.

Turning to the choice of a suitable indicator, or suite of indicators, we note that one of the most useful things to know about any ecosystem is the autotrophic biomass. This is precisely the deliverable from visible-range spectroradiometry of the sea (ocean colour), a method to produce spatial fields of autotrophic biomass, indexed as concentration of chlorophyll. Moreover, the biomass fields can be converted to fields of primary production using methods based on the first principles of plant physiology. Thus, we have two important ecosystem properties that can be surveyed at the scales of time and space required for ecological indicators at very little cost compared with the costs of conventional surveys. Such biological fields can be complemented by sea-surface temperature fields (an important property of the environment), with the same temporal and spatial resolution as for chlorophyll, also collected by remote sensing.

Recalling the goal of detecting ecosystem change, we note that a fundamental application of remotely-sensed data on ocean colour is the construction of time series. To effect this, all available (potentially daily) imagery within a chosen period (say, one week) is combined to produce a single image representative of conditions during that period. The resulting image is referred to as a composite image, and the period over which it is constructed will be the temporal resolution of the time series of composites. Creation of composites reduces the incidence of missing data points resulting from cloud cover or from any other difficulty in image processing.

The advantages of a time series are twofold. On the one hand it permits the temporal development of ecological processes to be realised and quantified: the seasonal dynamics are accessible. On the other it permits the comparison of conditions, or dynamics, between years (Fig. 1). Of course, the extent to which the dynamics are revealed depends on the temporal resolution of the series. But for the autotrophic biomass and the primary production, as developed from ocean colour, a resolution of one week in the composite images can usually be achieved, and this is quite sufficient to elucidate the seasonal dynamics. Access to the seasonal dynamics opens the way to other choices for ecological indicators. If we characterise the dynamics in some quantitative manner, we can base further ecological indicators on the phase relationships contained therein. These are objectively-determined quantities that can be expressed in standard units with a resolution of 1 km and 1 week. As computed from a time