

# Ecosystem science and the sustainable management of marine resources: from Rio to Johannesburg

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At the 1992 UN Conference on Environment and Development in Rio de Janeiro, nations were asked to adopt new approaches for the protection and sustainable development of marine environments and resources. A decade later, overexploitation continues unabated. Scientists advocate the adoption of ecosystem-based management systems to curtail overexploitation, but we first need to improve our understanding of the functioning of marine ecosystems. If research in the past decade was successful in identifying ocean structures and patterns, particularly at the species level, in the coming years we should concentrate on understanding the functioning of entire ecosystems, moving from an age of exploitation to a new era of sustainability. This review is based on a presentation at the 2001 UNESCO-IOC Global Conference on Oceans and Coasts at the Johannesburg 2002 World Summit on Sustainable Development (also known as Rio + 10), aimed at providing a progress assessment on oceans and coasts in the 10 years since the Rio conference, identifying new and continuing challenges, and formulating recommendations for the oceans and coasts agenda of the Johannesburg summit.

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The 1992 UN Conference on Environment and Development (UNCED) in Rio de Janeiro made clear that we had reached a turning point and indicated the necessity of moving towards global sustainable development in all aspects of human activity. Several of the documents adopted at UNCED specifically addressed the protection, rational use, and development of the marine environment and its resources.

Over the past decade, national and international bodies have developed legal frameworks and conducted management-related research towards addressing the UNCED vision, and have increasingly experimented with the application of the precautionary approach. This research has consolidated our understanding of the structure, and to some extent the functioning, of marine ecosystems, which is important in determining the relevance and effectiveness of the new legal landscape. This review high-

lights some research achievements and future avenues for investigation in marine ecosystems, in the context of the current legal framework on the use and protection of the marine environment. It is based on a presentation that was intended to provide guidance during preparations for the World Summit on Sustainable Development, in September 2002 in Johannesburg, South Africa.

## ■ The legal framework

Since UNCED, a number of legal and institutional changes have been implemented with respect to the exploitation, management, and sustainability of the marine environment. In particular:

- The United Nations Convention on the Law of the Sea of 1992, implemented in 1993
- The Convention on Biological Diversity of 1992, implemented in 1993 (a direct product of UNCED)
- The United Nations Framework Convention on Climate Change of 1992, implemented in 1993 (a direct product of UNCED)
- The Food and Agriculture Organization of the United Nations' (FAO) Compliance Agreement of 1993 (not yet enforced)
- The United Nations fish stocks agreements for straddling stocks and highly migratory species of 1995, implemented in 2001

In addition, a number of voluntary agreements have been approved. Although these are not enforced, there is an expectation that governments of fishing nations will

### In a nutshell:

- Global legislation has been unsuccessful in slowing the exploitation of marine ecosystems
- Ecosystem-based management systems (EBMS) have been proposed to solve some of the problems inherent in conventional management
- Ecosystems are highly dynamic, even in the absence of exploitation, but exploitation is also a driver of change
- We need to understand marine ecosystem functioning in order to replace marine exploitation with the sustainable use of marine resources

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include the spirit, principles, and specific mechanisms of these agreements in their national legislation. These are:

- The FAO Code of Conduct for Responsible Fisheries of 1993
- The Kyoto Declaration on Fisheries and Food Security of 1995
- The Rome Declaration on Implementation of the FAO Code of Conduct of 1999
- The Reykjavik Declaration on Responsible Fishing in the Marine Ecosystem of 2001

These agreements have provided a framework for the protection and management of the marine ecosystem that did not exist before UNCED, and which strongly emphasizes the role of scientific advice. However, there is a perception that a bottleneck is developing in the implementation of these instruments. The main reason is the difficulty in modifying and harmonizing national legislation to accommodate international agreements, and the problem is exacerbated in developing nations because of the costs involved in implementation.

One of the reasons why these new legal instruments were developed is because marine fisheries were, and still are, at a crossroads. In 1999, about 50% of all marine fisheries were fully exploited, 20% were overexploited, and a further 10% were depleted (FAO 2000). In the 1990s, the annual rate of increase of marine catches decreased to almost zero, and may even be negative (Watson and Pauly 2001), indicating that, on average, the world's oceans have reached their maximum production, estimated to be around 80–100 million metric tons (FAO 2000).

In recent years, these legal instruments have encouraged the development of ecosystem-based management systems (EBMS), which rely on a more holistic approach to resource management (Link 2002). The expectation is that EBMS will remove some of the impediments that conventional management has experienced, in particular the political unwillingness to heed scientific advice, which has led to the unsustainable use of many marine fisheries resources. But do we have the tools to develop and implement EBMS? The 2001 FAO Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem recognized that “the scientific basis for including ecosystem considerations in fisheries management needs further development and that there is incomplete scientific knowledge about the structure, functioning, components, and properties of the ecosystem, as well as about the ecological impact of fishing...”. We can interpret “further development” as the need for considerable additional research by fishing nations on the functioning of marine ecosystems.

#### ■ Financing research after Rio

In the run-up to UNCED in the late 1980s and early 1990s, several international marine research programs were developed, including the World Ocean Circulation

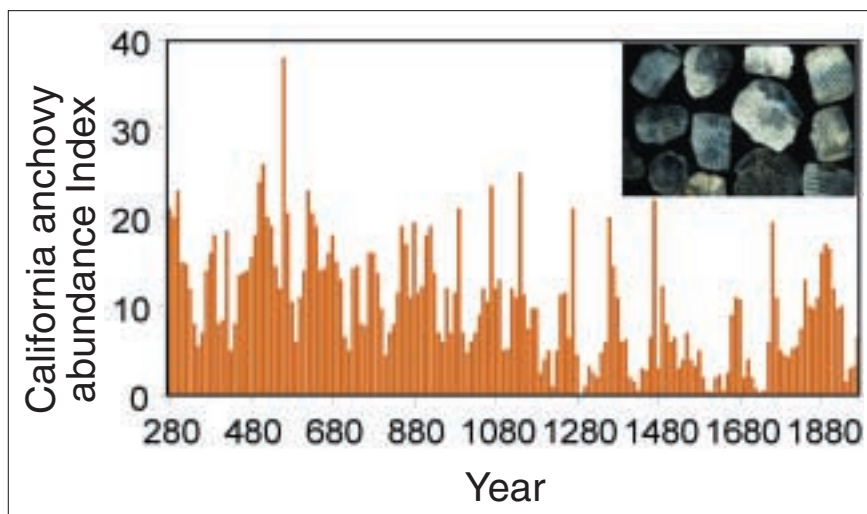
Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). These programs emerged out of the realization that we needed global and scientifically broad programs to resolve international issues with consequences at multiple scales. It is not possible to compile funding information from the entire research community, but in order to ascertain the commitment of funding agencies to these initiatives, we studied, as an example, trends in the allocation of funds by the USA National Science Foundation. The results suggested that the global concerns expressed at UNCED were indeed translated into real funding for global research during the 1990s. However, this added investment appears to have come at the expense of funding previously dedicated to disciplinary research rather than through additional funding (NRC 1999). Furthermore, the post-UNCED euphoria did not last long. As the first batch of global research programs moved towards their conclusion (WOCE was completed in 2002 and JGOFS will close down in 2003), new ones appeared, such as the Global Ocean Ecosystem Dynamics program (GLOBEC), but funding never reached the same level as for WOCE or JGOFS (P Taylor pers comm). There are concerns that this needs to change if we are to address the requirements of EBMS. In the transition from marine exploitation to sustainability, with the shift of objectives that this entails, additional research funding needs to be allocated to ensure resource sustainability. In order to identify the areas of research that require this extra funding, let us look at recent research achievements and identify the salient issues in the study of marine ecosystem functioning.

#### ■ Recent achievements and new research

A number of important scientific findings have been documented over the past decade concerning to the functioning of marine ecosystems. Without attempting an exhaustive review, I will highlight the most important of these and suggest key research issues that need to be resolved in the period following the 2002 Johannesburg World Summit.

#### Long-term patterns of change

Over the past decade, the role of human activity in causing change at the local, regional, and global level has been widely accepted. Petit *et al.* (1999) showed that, over the last 400 000 years, the biochemistry of the atmosphere has gone through a number of cycles, keeping concentrations of the major greenhouse gases, such as CO<sub>2</sub> and CH<sub>4</sub>, between 0–300 ppmv and 400–1200 ppbv, respectively. According to the Intergovernmental Panel on Climate Change, the current concentrations of these gases exceed these limits, with the expectation that, by 2100, measured values may increase by a factor of two or three (Houghton *et al.* 2001). As is well known, these gases are responsible for the warming of the earth's atmos-



**Figure 1.** Index of anchovy abundance from fish scales in sediment cores in the Santa Barbara Basin, California (from Baumgartner *et al.* 1992).

sphere, estimated at 0.6°C during the 20th century (Houghton *et al.* 2001). However, there has been less warming than the models predicted, because of the large capacity of the world's oceans to diffuse heat. Recent evidence indicates that a general warming of all the major oceans has been occurring over the past 50 years (Levitus *et al.* 2000; Gille 2002). How this warming will affect biological populations is the subject of considerable debate (Hughes 2000), partly because we know little about natural patterns of variability in marine biological populations in the absence of anthropogenic pressures. However, recent data suggest that extensive changes in the abundance of marine species over any given century have been common, even in the absence of anthropogenic pressures. This is seen, for example, in the trends governing anchovy abundance off the coast of California over the past millennia, based on records of scale deposition in the sediment (Baumgartner *et al.* 1992; Figure 1). Gradual, anthropogenically driven global changes are not likely to result in greater changes than those that occurred naturally (see also Finney *et al.* 2002). The perception is that the real effects of global change on marine ecosystems will be the result of interactions between anthropogenic pressures and natural cycles of variability.

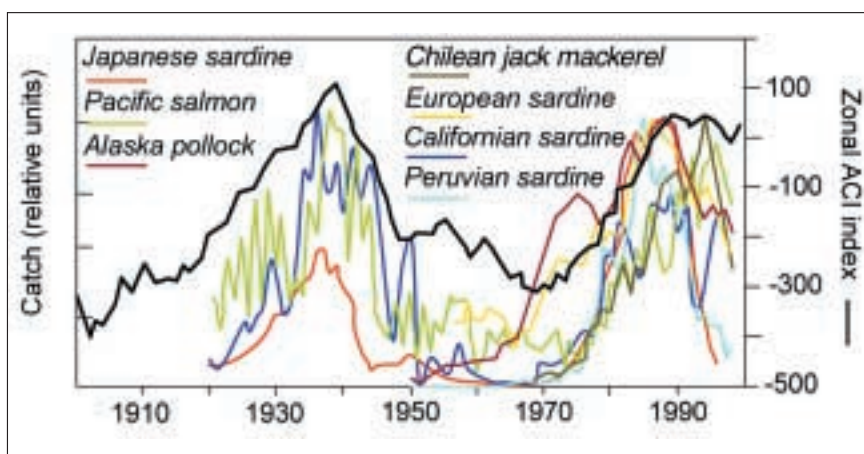
#### **Interdecadal cycles, teleconnections, and regime shifts**

The worldwide abundance of a number of pelagic (near-surface) fish species appears to follow synchronized cycles. It has been suggested that global temperatures modulate these cycles, with warm periods favoring sardines and cold periods supporting large anchovy fisheries (Lluch-Belda

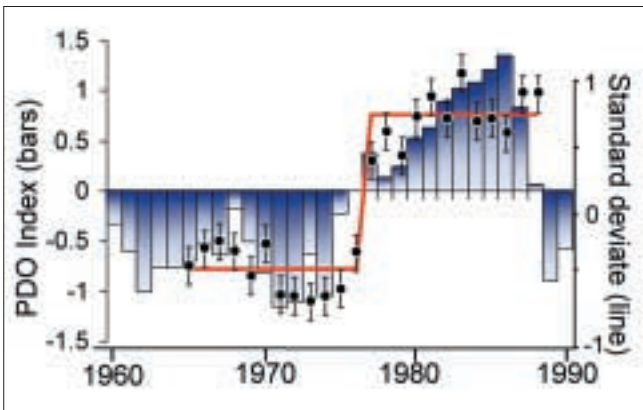
*et al.* 1992). Recently, similar synchronies have been observed in other nonpelagic species (Klyashtorin 1998; Figure 2). Using catch information as an indication of abundance for a dozen fish stocks, Klyashtorin (1998) classified them into two major groups: those displaying abundance peaks in the 1940s and 1990s (sardine-type species; Lluch-Belda *et al.* 1992), and those that peaked in the 1970s (anchovy-type species; Lluch-Belda *et al.* 1992). These patterns coincide with trends in the zonal and meridional components of the atmospheric circulation index, which reflect the strength and distribution of major pressure systems, and therefore wind, in the northern hemisphere. This sug-

gests that fish production may be modulated by natural environmental cycles acting on a global scale, despite the fact that fish production and fisheries are largely local-scale processes.

The idea that species have multidecadal cycles has recently been extended to the ecosystem and basin scales, linked to the concept of regime shifts. Using over 100 physical, chemical, and biological indices from the north east Pacific region, Hare and Mantua (2000) identified two regime shifts occurring in 1977 and 1989 (Figure 3). The biological consequences were widespread: over 70% of the fish catches off Alaska prior to 1977 were invertebrates, while finfish became dominant after 1977 (Jackson *et al.* 2001, Figure 4). The driving force behind these changes appears to be the Pacific Decadal Oscillation Index, which describes a decadal pattern of climate variability (Figure 3). Climatologically the shift included an intensification of the wintertime Aleutian Low, a year-round cooling of the Central North Pacific Ocean, and a warming of the coastal northeast Pacific Ocean and



**Figure 2.** Catch trends in several major commercial species and dynamics of the zonal Atmospheric Circulation Index (ACI), a measure of hemispheric air mass transport (modified from Klyashtorin 1998).



**Figure 3.** Results from a multivariate analysis of 100 environmental time series in the North Pacific, showing the 1977 regime shift, superimposed on the Pacific Decadal Oscillation Index of 1960–90. Standard error of the 100 time series is illustrated for each year (modified from Hare and Mantua 2000).

Bering Sea. Consequences included decreases in zooplankton abundance off California, declines in Alaskan shrimp and most West Coast salmon populations, and increases in most Alaskan salmon stocks. Interestingly, the second regime shift, in 1989, was not a simple reversal of ecosystem conditions established after 1977. What causes ecosystems to change state is unclear; Scheffer *et al.* (2001) hypothesized that they may have a limited number of stable states to which they gravitate. A small change in environmental conditions may cause an ecosystem collapse. Significantly, a reversal of these conditions would not return the system to its previous equilibrium. This hypothesis requires further development and additional data for adequate testing.

#### **Trophic cascades, food webs, and biodiversity**

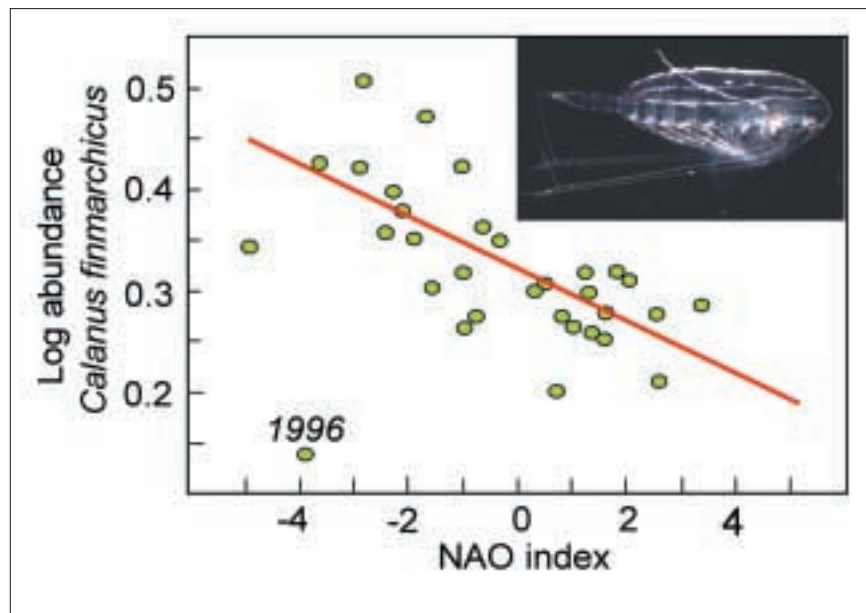
Regime shifts destabilize entire communities in response to some external pressure. Such pressures can cause changes at the top or the bottom of the food web, and these could be expressed at all levels, in cascade fashion. Links between long-term trends seen in North Atlantic westerly winds and four marine trophic levels in the 1980s suggested a cascading effect (Aebischer *et al.* 1990). Dramatic biomass changes were also observed in the North Sea around 1988, from phytoplankton to fish species, coinciding with the highest positive North Atlantic Oscillation Index (NAO) records for more than a century (Reid *et al.* 2001). Whether this is indicative of a trophic cascade or of a regime change is unknown. Alterations in the convection of deep water from the Greenland Sea to the Labrador Sea after 1988 (Heath *et al.* 1999; Dickson *et al.* 2002) and increases in the flow of oceanic water into the North Sea through the Shelf Edge Current (Holliday and Reid 2001) appear to be the main drivers for these changes.

We also do not know how resilient food webs are to bottom-up or top-down changes. Further research is also



**Figure 4.** Changes in species composition of catches in a small-mesh bottom trawl in Pavlof Bay, Alaska, through the regime shift of the mid-1970s (from Botsford *et al.* 1997).

needed into the circumstances in which ecosystems will readjust themselves slowly and in coordination, and when they switch state. Scheffer *et al.* (2001) has suggested that ecosystems under stress might be more susceptible to regime shifts, as a result of exploitation or environmental pressure. These authors also suggested that biodiversity might play a role in determining the stability and resilience of ecosystems (but see Pfeisterer and Schmid 2002). Rice (2001) noted that ecosystems in which a sin-



**Figure 5.** Relationship between annual abundance of *Calanus finmarchicus* in the northeast Atlantic and the North Atlantic Oscillation index (from Fromentin and Planque 1996).

gle species or group of species controls both the dynamics of its predators and prey may be more susceptible to collapses if heavily exploited during low production regimes. These ideas have not yet been investigated in the field, an essential step for producing biodiversity and exploitation scenarios for the coming years.

#### Detecting change and identifying causes

Detecting change in variable environments is easy, but identifying the causes can be very difficult. Yet global change research requires that the processes linking causes and effects be clarified so that we can predict future scenarios for ecosystem functioning. For example, Fromentin and Planque (1996) reported that, between 1948 and 1996, the abundance of the copepod *Calanus finmarchicus* was inversely related to the NAO Index (Figure 5). The NAO measures the difference between the high pressure system in the Azores and the low pressure system in Iceland, and is directly responsible for interannual weather change patterns over Western Europe and the East Coast of North America. Fromentin and Planque (1996) suggested that this relationship was driven by changes in circulation patterns at the basin level. However, after a long period of positive NAO values, the relationship broke down in 1996, when a reversal to negative NAO was not followed by higher copepod abundance that year or any subsequent years (B Planque pers comm). Heath *et al.* (1999) concluded that the cause of the breakdown was a decline in the production of Norwegian deep-sea water, and the subsequent decline in the supply of copepods to coastal regions of the UK. It will take several years of persistent deep convection in the Greenland Sea to restore the deep-water overflow and stimulate a recovery in *Calanus finmarchicus* (Heath *et al.* 1999). Understanding the

processes linking cause and effect has helped us move from the static regression, copepods versus NAO, to a more dynamic and realistic predictive scenario, involving a study of the dynamics of the North Atlantic ecosystem.

#### Ecosystem effects of fishing

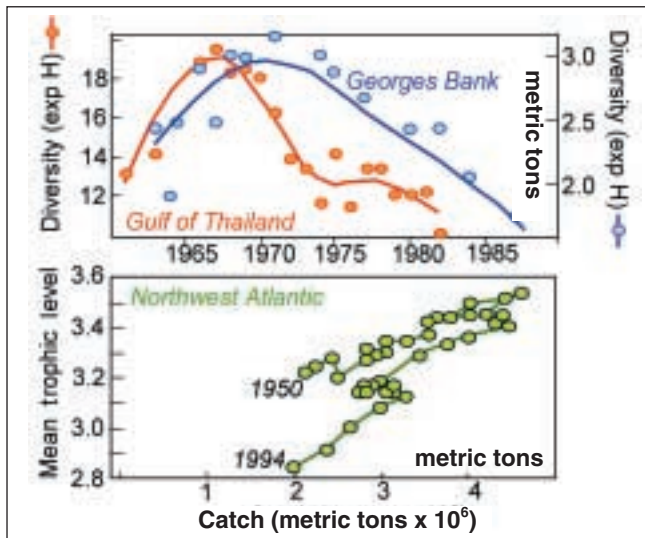
Almost 90 million metric tons of fish are extracted from the sea each year, excluding discarded bycatch; this provides the equivalent of about 10 kg per person per year worldwide (FAO 2000). The ecological consequences of extracting such a vast amount of biota are evident. Selective exploitation can change the size and age structure of populations if the frequency of extraction is shorter than the generation time of some of the species involved. In the Gulf of Thailand, for example, the depletion in numbers of large fish has resulted in a

consistent reduction in the trophic level of the catches (Christensen 1998), so that the fishery is now reduced to producing animal feed. Similar trends have been observed in other heavily exploited systems (Pauly *et al.* 1998; Figure 6), reflecting both changes in the mean size of the fish caught and the removal of top predators. Changes in species diversity (a measure of community structure and ecosystem resilience) in the Yellow Sea (Jin and Tang 1996), the Gulf of Thailand, and the Georges Bank (Hall 1999) follow similar patterns: diversity increases during the early stages of the fishery, and then declines dramatically (Figure 6). Fishing impacts are also known to cascade through the food chain, although separating natural and human-induced changes is not always possible (Jennings and Kaiser 1998). In addition, between 17.9 and 39.5 million metric tons of mostly dead fish (Alverson *et al.* 1997) are discarded annually by commercial fisheries, a practice that may severely affect the energy flow in those ecosystems.

In summary, fishing is having marked effects on the structure of many marine ecosystems, generally the most productive ones. These structures developed over long periods of time, through complex multispecific interactions, trophic links, density-dependent responses, and competition for space and food. We need to quantify these anthropogenically driven changes and their consequences in terms of ecosystem functioning, turnover rates, matter fluxes, and so on, and to determine whether they are reversible, and if so over what time scales.

#### ■ EBMS for a sustainable future

Ecosystems cannot be fully managed because our grasp of their complexity is, and will remain, limited for the foreseeable future. However, the concept of EBMS implies



**Figure 6.** Anthropogenic changes in marine ecosystem structure. (top) Trends in the Shannon-Wiener diversity index in the Gulf of Thailand (from Pauly 1987) and St Georges Bank (from Solow 1994), and (bottom) mean trophic level versus catch in the Northwest Atlantic, 1950–1994 (from Pauly et al. 1998).

that we should manage specific components of the system, while monitoring the consequences of such management for the entire ecosystem. Some basic principles apply:

- Ecosystems have thresholds and limits which, when exceeded, can irreversibly affect their structure
- Ecosystem components are linked and interact within and between ecosystems, along multiple scales
- Diversity is important to ecosystem functioning
- Ecosystems change with time and have no boundaries (EPAP 1999)

The research discussed here should underpin further development of the EBMS concept, and could form the basis of new ecosystem theory. To facilitate this, we need to support the following global change research through the following cross-cutting issues.

#### Support global observing systems

To develop emerging concepts, such as basin-scale regime shifts, the apparent connectivity between ecosystems, or the cyclical nature of ocean productivity, requires a global monitoring of physical, chemical, and biological properties. Most of our past biological oceanographic advances have been driven temporally and spatially by limited data extrapolated to larger scales. Systems such as the Global Ocean Observing System would provide the necessary hard data to support this research properly.

#### Collect better fish and fishery statistics

Catch statistics compiled by the Food and Agriculture Organization have been used as a measure of species

abundance, providing data for the development of hypotheses on the connectivity of production cycles at the species level (Klyashtorin 1998). Most commercial fisheries are now regulated by catch or effort controls, so future reported catches will no longer be useful in gauging abundance. We need to establish databases of estimated species abundance and resource management approaches, possibly also through the FAO. Such an inventory does not yet exist, but it would be of considerable value. Resistance from countries wishing to protect their management systems could be addressed by allowing a delay of 2–5 years in reporting.

#### Develop long-term comparative studies

Complex biological systems are controlled by their top predators (top-down ecosystems, Steele and Henderson 1998), by their bottom producers (bottom-up ecosystems; Pace et al. 1999), or by a number of key species in the middle (middle-outwards or wasp-waist ecosystems; Cury et al. 2000). It has become apparent that the way an ecosystem is structured is important in determining whether specific climatic, oceanographic, or biological factors will influence its dynamics, and if so, in what way. To apply EBMS, therefore, it is essential that we have methods for quantifying and comparing ecosystems holistically. These methods would take into account the biotic and abiotic factors that determine changes in the carrying capacity (eg food availability), trophic interactions (eg predation), and habitat suitability (eg temperature regimes) of a given ecosystem, perhaps in the form of annual or multi-annual ecosystem reports. These reports would summarize trends in ecosystem indicators, and could form the basis for comparisons between ecosystems. Such reports are already available, in a preliminary form, for the North Atlantic ([www.ices.int](http://www.ices.int)) and are planned for the North Pacific ([www.pices.int](http://www.pices.int)), albeit for a more restricted purpose. As they develop and mature, these ecosystem reports could play a vital role in the development of hypotheses regarding fluctuations, interactions, and feedbacks among agents and impacts of change, at many scales, including seasonal, multidecadal, species, or ecosystem. In addition, they might include a number of individual “report cards” tailored for the management of specific exploited stocks.

We will be the ultimate receivers of changes in marine ecosystem structure. Of obvious importance is the need to reevaluate our use of marine resources should climate change and our own activities threaten the food supply. Understanding our changing marine ecosystem will require the development of integrative science that addresses the synergies, interactions, and nonlinearities that we see. This work must transcend the disciplinary boundaries between the natural and social sciences, and possibly even venture into the social sciences. In the aftermath of the Johannesburg Earth Summit (Table 1) we need to focus on the development of this science, which

**Table 1. The changing scientific scenario for marine ecosystem science between UNCED in Rio de Janeiro in 1992 and the Johannesburg World Summit on Sustainable Development (WSSD) in 2002.**

UNCED (Rio de Janeiro 1992)	WSSD (Johannesburg 2002)
Ecosystem structure	Ecosystem functioning
Describing patterns	Resolving processes
Focus at species level	Focus at ecosystem level
Era of exploitation	Era of sustainability

must be rooted in the concept of ecosystem sustainability, in order to protect our life-support systems and support the integrated management of our planet.

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