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INTRODUCTION TO ECOSYSTEM BASED FISHERIES MANAGEMENT AND ECOPATH MODELLING

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Introduction

Fish populations are an integral part of marine ecosystems. Historically, fish population dynamics have been studied as single species, for example as mackerel, shrimp or sardine, and almost always in isolation from the system in which they exist. In recent years, however, there has been growing awareness that traditional approaches to managing fisheries are incomplete and partially unsuccessful. Sustainable use of living marine resources must consider both the impacts of the ecosystem on the living marine resources, and the impacts of fishery on the ecosystem. This holistic approach to fisheries management has been termed as '*ecosystem-based fisheries management*'. The principles of Ecosystem-Based Fisheries Management are: '1. Maintaining the natural structure and function of ecosystems, including the biodiversity and productivity of natural systems and identified important species, is the focus for management. 2. Human use and values of ecosystems are central to establishing objectives for use and management of natural resources. 3. Ecosystems are dynamic; their attributes and boundaries are constantly changing and consequently, interactions with human uses also are dynamic. 4. Natural resources are best managed within a management system that is based on a shared vision and a set of objectives developed amongst stakeholders. 5. Successful management is adaptive and based on scientific knowledge, continual learning and embedded monitoring processes'.

A lot of attention has been directed recently at assessing the impacts of fisheries on whole marine ecosystems (ICES, 1998, 2000; Frid et al., 1999b; Hall, 1999a, b). This has in part been driven by the need to ensure conservation of biological diversity and sustainable use of the biosphere, key provisions of the convention agreed at the UN Rio summit (Tasker et al., 2000). The utilization of sound ecological models as a tool in the exploration and evaluation of ecosystem health and state has been encouraged and endorsed by the leading bodies in ecosystem-based fisheries research and management (NRC, 1999; ICES, 2000). The potential of the available dynamic ecosystem models to make measurable and meaningful predictions about the effects of fishing on ecosystems has not however been fully assessed.

Ecological factors

Harvesting alters ecosystem structure in ways that are only beginning to be understood. It is argued that long-term heavy commercial harvesting is likely to shift the ecosystem to high-turnover species with low trophic levels (Pitcher and Pauly, 1998). The biological mechanism underlying species shifts is that the relatively large, long-lived fishes which have low mortality rates are more strongly affected by a given fishing mortality rate than are smaller fishes which are part of the same community. A second shift-inducing biological mechanism is habitat degradation caused by various fishing gears especially bottom trawls. Here, the effect is through destruction of bottom structure, depriving benthic fishes of habitats and prey.

Thirdly, the above and the fishery-induced reduction of predatory pressure by benthic fish, may then lead to an increase of small pelagic fish and squids, which becomes available for exploitation. This may mask the decline in catches of the demersal groups. In the Gulf of Thailand, in Hong Kong Bay and other areas of the South China Sea, extremely heavy trawl pressure has resulted in a shift from valuable demersal table fish such as sciaenids, groupers and snappers to a fishery dominated by small pelagics used for animal feed and invertebrates such as jellyfish and squids.

These mechanisms almost often lead, through a positive feedback loop, to a fourth biological mechanism: harvesting small pelagic fish species at lower trophic levels reduces the availability of food for higher trophic levels, which then decline further, releasing more prey for capture by a fishery that finds its targets even lower down the food web, a process now occurring throughout the world (Pitcher and Pauly, 1998). Some examples of such documented species shifts in exploited multispecies fish communities are shown in Table 1.

It has also been observed that fishes evolve or change their life histories in response to selective fishing mortality, for e.g., halving of the size of mature Chinook salmon. In this semelparous species early maturity means less time at risk of being caught and therefore, higher fitness. This species has been intensively managed for over 80 years using the best that single species quantitative science can offer, and yet Chinook salmon are on decline.

Table 1. Examples of documented shifts towards smaller, high-turnover species in exploited multispecies communities (modified from Pitcher and Pauly, 1998)

Fishing grounds/ Stocks (period)	Documented species shift
Gulf of Thailand Demersal stocks (1960-1980)	Overall biomass reduced by 90%; residual biomass dominated by trash fish
Philippine shelfSmall pelagics (1950-1980)	Gradual replacement of sardine-like fishes by anchovies
Carigara Bay, Philippines All fish (1970-1990)	Fish replaced by jellyfish, now an export item
Black Sea table fish	Small pelagics and jellyfish replace large
North Sea and haddock threatened; demersal favoured	Halibut and small sharks extinct; cod omnivores and small pelagics
Humboldt Current, Chile favoured	Large hake depleted, small pelagics
North Pacific followed by huge trawl fisheries: Pollock	First marine mammal depletions, favoured
South China Sea, Hong Kong small pelagics bulk of fishery	Croakers and groupers almost extinct;

Socio-economic factors

One of the main socio-economic mechanisms, which contribute to species shift, is increasing prices, both for traditional high-value species and for trash species. Such price increases are effective in masking the economic consequences of fishing at lower trophic levels.

**Single species assessments**

The tools developed for single species population dynamics are an essential part of any new methodology. Detailed information on growth, mortality and recruitment schedules and their associated errors and uncertainties are essential for the implementation of the ecosystem approach advocated in the Rio summit.

When considering the management of single components of the ecosystem, such as the target fish stocks, it is possible to set target and limit reference points for particular measurable properties of the species. For example, the implementation of precautionary fisheries management in the North Atlantic has

progressed through the setting of reference points for various measures of the status of the exploited species, e.g. the spawning stock biomass (SSB). Two types of reference point are considered - a limit reference point and a target reference point (Fig.1). Management measures are aimed at achieving the target reference point in the medium term and ensuring that the limit reference point is never exceeded.

In theory, it should be possible to apply reference points to any or all taxa in the ecosystem. ICES (2000) have contended that even if this was practical for a significant number of taxa, it may not ensure adequate protection of all the ecosystem components at risk. There is a need, therefore, to develop reference points for system level emergent properties as a measure of ecosystem health (Hall, 1999a; Gislason et al., 2000).

Fig.1. Illustration of target, threshold and limit reference points with regard to spawning stock biomass (from Hall and Mainprize, 2004)
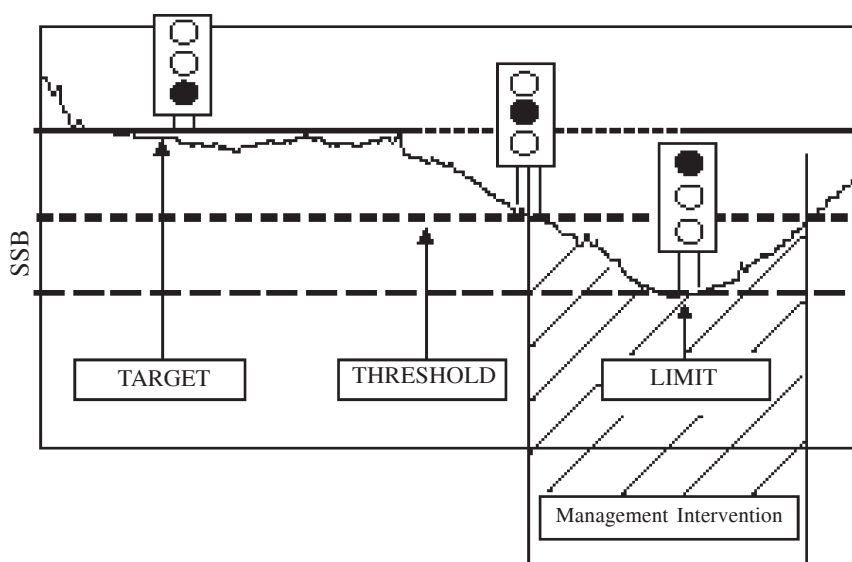
Ecosystem modelling

There are many recent developments in building of trophic models of aquatic ecosystems. Such modelling can now be performed more rapidly and rigorously than ever before, providing a basis for viable and practical simulation models that have real predictive power (Christensen and Pauly, 1993; Walters et al., 1997). This was made possible by the development of ECOPATH (Polovina, 1984; Christensen and Pauly, 1992), for construction of mass-balance models of ecosystems, based mainly on diet composition, food consumption rates, biomass and mortality estimates.

Such ecosystem models can describe the biomass flows between the different elements of the exploited ecosystems, and can provide answers to 'what if' questions regarding the likely outcome of alternate fishing policies. The ECOPATH suite of software has now been modified (Walters et al., 1997, 2000) to include ECOSIM (simulation module) and ECOSPACE (spatial module). These new routine have not only increased the quantitative power of the approach, but have also allowed qualitatively new questions to be asked.

Ecopath applications to ecosystems, ranging from low latitude areas to the tropics, and from ponds, rivers, and lakes to estuaries, coral reefs, shelves, and the open sea, but all using the same metrics, allowed identification of several general features of aquatic ecosystems.

Multivariate comparisons demonstrated the basic soundness of E. P. Odum's (1969) theory of ecosystem maturation (Christensen, 1995b), including a confirmation of his detailed predictions regarding ecosystems near carrying capacity (Christensen and Pauly, 1998). Conversely, this theory can now be used to predict the effect of fisheries on ecosystems, which tend to reduce their maturity, as illustrated by the comparison of Ecopath models for the Eastern Bering Sea in the 1950s and early 1990s (Trites *et al.*, 1999a, b), and to guide ecosystem rebuilding strategies implied in ''Back to the Future'' approaches (Pitcher, 1998; Pitcher *et al.*, 2000).

The importance (relative to fishing) of predation by fish and marine mammals within marine ecosystems as suggested by complex models in a few areas (North Sea: Andersen and Ursin, 1977; North Pacific: Laevastu and Favorite, 1977) was confirmed globally by Ecopath models (Christensen, 1996; Trites *et al.*, 1997).

Identification of trophic levels as functional entities rather than as concepts for sorting species (Lindeman, 1942; Rigler, 1975) implied the use of non-integer values (computed as 1+ the mean trophic level of the preys, as proposed by Odum and Heald, (1975) that express degree of omnivory (Christensen and Pauly, 1992a), i.e., the extent to which feeding occurs at different trophic levels (Pimm, 1982). Also, trophic level estimated from analyses of stable isotopes of nitrogen has been shown to correlate well with estimates from Ecopath models (Kline and Pauly, 1998).

Estimates of transfer efficiencies between trophic levels (Christensen and Pauly, 1993b; Pauly and Christensen, 1995), previously a matter of conjecture usually pertaining to single-species populations or even to studies of a few individual animals (Slobodkin, 1972), differed radically from earlier guesses by ecosystem types (Ryther, 1969) used for inferences on the potential yields of fisheries (Pauly, 1996), even though the mean was unsurprising (about 10%; Morowitz, 1991).

Performance measures

It is generally agreed that reductions in single species fishing mortality levels is perhaps the most significant step one could take towards ensuring the persistence of marine ecosystems (Hall and Mainprize, 2004). It is also clear that ecosystem-based fisheries management is still in its formative years, although substantial developments have been seen in some countries and regions. Among these, North America, Antarctica, Europe, Australia and New Zealand are the most notable.

Table 2. The six principles for an ecosystem based fisheries management approach (adapted from Inter-agency Marine Fisheries Working Group, 2002)

Principle	Description
Ecosystem identification	The ecosystem that fisheries will be managed within need to be defined on the basis of the main physical, biological and human dependency relationships
Clear objectives	Objectives for fisheries management shall have regard to local and national needs, and management should be decentralized to the maximum extent possible
Long term benefits	Ecosystem based management should aim for long term benefits – management should look to restore stocks to levels that are capable of delivering optimal yields over the long term; and achieving such yields should not compromise other marine species and habitats. Management should also aim to support biological biodiversity
Incentives aligned with and ecosystem based approach	Incentives should be realigned to support aims of the ecosystem based approach - incentives and financial support needs to be redirected from fisheries based approach that aim at increasing fishing efficiency to those that make concerted efforts to those that promote restoration of

	fish stocks to optimal yield levels and which support responsible fishing practices in sensitive marine areas
Easily assessed information and alternate management options	Information necessary to implement the ecosystem-based approach should be made available to all. Where information is insufficient, adaptive management and the precautionary approach should be followed. If the outcome falls short of what was intended the management decisions should be suitably altered – proactive management

Unfortunately, despite the legislative imperative and clearly articulated principles (Table 2), arriving at an operational framework for an ecosystem-based approach to fisheries management is fraught with difficulties. This difficulty is due, not only to the inherent challenge in establishing and quantifying the effects of fishing at an ecosystem level, but also due to the social and political dimensions associated with harvesting fisheries at an environmentally sustainable level.

An overview of Ecopath & Ecosim

The Ecopath software is a simple approach for analyzing trophic interactions in fisheries resources systems (Christensen and Pauly 1992a,b, 1995). Ecopath is based on the earlier work of Polovina (1984), and is being widely applied to aquatic systems (Christensen and Pauly 1993, Pauly and Christensen 1995). It is a mass-balance approach that describes an ecosystem at steady-state for a given period. Further development of this steady-state model has resulted in a dynamic ecosystem model called Ecosim that is capable of simulating ecosystem changes over time (Walters et al., 1997). Ecopath and Ecosim represent all of the major components of the ecosystem, and their feeding interactions, but are relatively simple. These kinds of models readily lend themselves to answering simple, ecosystem wide questions about the dynamics and the response of the ecosystem to anthropogenic changes. Thus, they can help design policies aimed at implementing ecosystem management principles, and can provide insights into the changes that have occurred in ecosystems over time. Ecopath models rely on the truism that:

Production = biomass accumulation + fisheries catch + mortality due to predation + other mortality + loss to adjacent systems.

This applies for any producer (e.g., a given fish population) and time (e.g., a year or season). Groups are linked through predators consuming prey, where:

Consumption = production + non-assimilated food + respiration.

The implication of these two relationships is that the system or model is mass balanced (i.e., biomass is 'conserved', or accounted for in the ecosystem). This principle of mass conservation provides a rigorous framework – formalized through a system of linear equations – through which the biomass and trophic fluxes among different consumer groups within an ecosystem can be estimated (Christensen and Pauly 1995). Constructing an Ecopath model emphasizes ecological relationships rather than mathematical equations. All that is required are the types of data that are routinely collected by fisheries scientists and marine biologists. The model can incorporate and standardize large amounts of scattered information – information that might have otherwise languished in scattered journals, reports and filing cabinets (Christensen and Pauly 1995).

Ecopath is essentially a large spreadsheet that is simultaneously keeping track of all the species and all the feeding interactions occurring within the ecosystem. It describes the ecosystem at one point in time. Ecosim, which is based on the Ecopath equation, simulates how a change in one or more components might affect the ecosystem over time.

Ecopath and Ecosim have been widely applied in recent years. More than 80 Ecopath systems have so far been published worldwide. They span a diversity of systems including upwelling, shelves, lakes and

ponds, rivers, open oceans and even terrestrial farming systems (see Christensen and Pauly 1992a,b, 1995; Walters et al. 1997; and the Ecopath home page at http://www.ecopath.org).

Principles of the Ecopath Model

The core routine of Ecopath is derived from the Ecopath program of Polovina (1984), and since modified to make superfluous its original assumption of steady state. Ecopath no longer assumes steady state but instead bases the parameterization on an assumption of mass balance over an arbitrary period, usually a year. In its present implementation Ecopath parameterises models based on two master equations, one to describe the production term and one for the energy balance for each group.

The first Ecopath equation describes how the production term for each group (i) can be split in components. This is implemented with the equation,

Production = catches + predation mortality + biomass accumulation + net migration + other mortality;

or, more formally,

$$P_i = Y_i + B_i \cdot M2_i + E_i + BA_i + P_i \cdot (1 - EE_i) \qquad \text{Eq.1}$$

where Pi is the total production rate of (i), Y_i is the total fishery catch rate of (i), $M2_i$ is the total predation rate for group (i), B_i the biomass of the group, E_i the net migration rate (emigration - immigration), BA_i is the biomass accumulation rate for (i).

This formulation incorporates most of the production (or mortality) components in common use, perhaps with the exception of gonadal products. Gonadal products however nearly always end up being eaten by other groups, and can be included in either predation or other mortality.

Eq. 1 can be re-expressed as

$$B_i \cdot (P/B)_i \cdot EE_i - \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} - Y_i - E_i - BA_i = 0 \quad \text{Eq. 2}$$

where: P/Bi is the production/biomass ratio, Q/Bi is the consumption / biomass ratio, and DCj i , is the fraction of prey (i) in the average diet of predator (j).

Of the terms in Eq. 2 the production rate, Pi, is calculated as the product of Bi, the biomass of (i) and Pi/Bi, the production/biomass ratio for group (i). The Pi/Bi rate under most conditions corresponds to the total mortality rate, Z, see Allen (1971), commonly estimated as part of fishery stock assessments. The other mortality is a catch-all term including all mortality not elsewhere included, e.g., mortality due to diseases or old age, and is internally computed from,

$$M0_i = P_i \cdot (1 - EE_i)$$

where EEi is called the ecotrophic efficiency of (i), and can be described as the proportion of the production that is utilized in the system. The production term describing predation mortality, M2, serves to link predators and prey as,

$$M2_i = \sum_{j=1}^{n} Q_j \cdot DC_{ji} \quad \text{Eq. 3}$$

where the summation is over all (n) predator groups (j) feeding on group (i), Qj is the total consumption rate for group (j), and DCji is the fraction of predator (j) diet contributed by prey (i). Qj is

calculated as the product of Bj, the biomass of group (j) and Qj/Bj, the consumption/biomass ratio for group (j).

An important implication of the equation above is that information about predator consumption rates and diets concerning a given prey can be used to estimate the predation mortality term for the group, or, alternatively, that if the predation mortality for a given prey is known the equation can be used to estimate the consumption rates for one or more predators instead.

For parameterization, Ecopath sets up a system with (at least in principle) as many linear equations as there are groups in a system, and it solves the set for one of the following parameters for each group: biomass; production/biomass ratio; consumption/biomass ratio; or ecotrophic efficiency.

The other three parameters along with following parameters must be entered for all groups: catch rate; net migration rate; biomass accumulation rate; assimilation rate; and diet compositions.

It was indicated above that Ecopath does not rely on solving a full set of linear equations, i.e., there may be less equations than there are groups in the system. This is due to a number of algorithms included in the parameterization routine that will try to estimate iteratively as many missing parameters as possible before setting up the set of linear equations.

Further Reading

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