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Multispecies Management Strategies
for Capture Fisheries

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Tony Pitcher and Kevern Cochrane

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Director's Foreword

Ecosim in the Land of Cockayne

There is a famous Breughal engraving, 'Big Fish Eat Little Fish', that illustrates a marine food web by showing how the stomach of each size of fish contains fish of the smaller size class below. I use it to dramatise trophic relationships and, many years ago, it made a neat cover for my textbook (Pitcher and Hart 1982). One student later said that the book cover taught him all he knew. Another Breughal painting is reproduced opposite in hopes it will be equally instructive.

Like the Breughal engraving, Ecopath models take all trophic relationships within an aquatic ecosystem into account, and the approach will be familiar to many readers of Fisheries Centre Research Reports, being the subject of 5 previous issues from 1996 (see below). Ecopath, the dynamic version of Ecopath (Walters *et al.* 1997, 2000) has recently been endowed with routines that not only simulate the consequences of changes in fisheries for all elements in the ecosystem, but can also search for fishing rates that will maximize ecological, social or economic goals. The first report of this important advance made by Carl Walters is presented here.

This new facility has interested FAO because it could lead to a way of managing multispecies fisheries that takes into consideration all elements of the ecosystem, not just those that are subjected to fishing. Hence, the Fisheries Centre and FAO decided to hold a workshop to explore the potential of the new software, and the papers in this report are the result.

Back to that Breughal. The 'Land of Cockayne' is a derisive medieval comment on those who imagine themselves in a paradise where food and luxuries are so easily obtainable that life is comprised of little more than a happy indolence. Or boast that they are in such a place. As Breughal's painting shows (above), Cockayne is evidently such a fool's paradise. The term 'Cockayne' probably derives from 'cake' (OED), and there are similar terms in medieval French. It gave rise to 'Cockneys', inhabitants of London noted for boasting of the miraculous nature of their city, and a similar idea



The Land of Cockayne, by Pieter Breughal the Elder, 1567. As well as illustrating a Fool's Paradise (note the egg on legs and the walking roast pig), the painting also shows how some of the workshop participants felt after a week of simulations.

Oil on panel, 52 x 78 cm, Alte Pinakothek, Munich.

also became the 'Big Rock Candy Mountain' of US hobo lore.

What's the moral here? Well - it is all too easy to be seduced by these elegant simulations. The 'Land of Cockayne' is intended to provide a plangent warning that we should continually check simulation results with the real world. And not be tempted to boast that Ecosim optima place us in a far better world. It is a reality check.

The Fisheries Centre Research Reports series publishes results of research work carried out, or workshops held, at the UBC Fisheries Centre. The series focusses on multidisciplinary problems in fisheries management, and aims to provide a synoptic overview of the foundations, themes and prospects of current research.

Fisheries Centre Research Reports are distributed to appropriate workshop participants or project partners, and are recorded in the Aquatic Sciences and Fisheries Abstracts. A full list appears on the Fisheries Centre's Web site, www.fisheries.ubc.ca. Copies are available on request for a modest cost-recovery charge.

Tony J. Pitcher

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Executive Summary

This report comprises the edited proceedings of workshop held at the Fisheries Centre, University of British Columbia in July 2000, jointly sponsored by FAO, Rome and the government of Japan.

This is the first published account of new Ecosim policy search software that aims to find fishing rates that maximize objective functions for economic, ecological, employment or mixed goals. Two papers set out the numerical basis for the software and the procedure that was adopted for the workshop case studies.

The report contains 18 case study papers exploring the use of the ecosim policy software. Papers examine fisheries and their ecosystems in the Strait of Georgia (BC), the Bali Strait (Indonesia), the North Sea, The Faroe Islands, Hong Kong, Lake Malawi, Newfoundland, Port Philip Bay (Tasmania), Prince William Sound (Alaska), the San Matias Gulf (Argentina), the Scotian Shelf (Canada), Southern Benguela (South Africa), Campeche Sound (Mexico), Gulf of California (Mexico), the Caribbean (Columbia).

Searching for optimum fishing strategies for fishery development, recovery and sustainability

Carl J. Walters, V. Christensen
and Daniel Pauly

Fisheries Centre, UBC

Abstract

Policy may be defined as an approach towards reaching a broadly defined goal. In fisheries, policies are often implemented via total allowable catches, TACs, that are recalculated annually, and through regulations that affect fleet and deployment. The task of fisheries scientists should be to advise both on policy formulation and on its implementation. However, so far ecosystem-based policy explorations have rarely been conducted. This can, however, now be addressed by the recent development of a policy exploration routine for the Ecopath with Ecosim approach and software. The paper gives an overview of the background for the policy search, and how it has been implemented. A brief overview of a new routine for examining uncertainty in the management process is also included.

On Policy Exploration using Ecopath with Ecosim (EwE)

A central aim of fisheries management is to regulate fishing mortality rates over time so as to achieve economic, social, legal and ecological sustainability objectives. An important dynamic modeling and assessment objective is to provide insight about how high these mortality rates should be, and how they should be varied over time (at least during development or recovery from past overfishing). We cannot expect models to provide very precise estimates of optimum fishing mortality rates, but we should at least be able to define reasonable and prudent ranges for the rates. The impacts of alternative time patterns of fishing mortalities can be explored using two different approaches in Ecosim:

1. Fishing rates can be 'sketched' over time in the Ecosim simulation interface, and simulated results (catches, economic performance indicators, biomass changes) examined for each sketch. This is using Ecosim in a 'gaming' mode, where the aim is to encourage rapid exploration of options.
2. Formal optimization methods can be used to search for time patterns of fishing rates (actually, relative fishing efforts by fishing fleet/gear types), which would maximize particular performance

measures or 'objective functions' for management.

These approaches can be used in combination, e.g. by doing a formal optimization search then 'reshaping' the fishing rate estimates from this search in order to meet other objectives besides those recognized during the search process.

The first of these approaches is what has up to now been the standard simulation form in Ecosim, and does not require further description here, (see Walters *et al.*, 1997; Christensen *et al.*, 2000; Walters *et al.*, 2000). The newly added formal optimization involves three steps:

1. Define blocks of fleet/year groupings to be included in the search procedure;
2. Define objective function weights for the four optimization objectives:
 - (i) net economic value (total landed value of catch minus total operating cost to take this landed value);
 - (ii) employment (a social indicator, assumed proportional to gross landed value of catch for each fleet with a different jobs/landed value ratio for each fleet);
 - (iii) mandated rebuilding of target species (obtained by setting a threshold biomass for the relevant species relative to their biomass in Ecopath);
 - (iv) ecological 'stability' (measured by assign-ing a weighting factor to each group based on their longevity, and optimizing for the weighted sum).
3. Invoke the search procedure by clicking the search button.

When a search has been completed, the resulting 'optimum' fishing rates by year/fleet block are transferred to the Ecosim 'Temporal Simulation', where the optimized fishing rates will have replaced the baseline (or previously sketched) relative efforts by fleet/gear type.

Methodology

Invoking the search option causes Ecosim to use a nonlinear optimization procedure known as the Davidson-Fletcher-Powell (DFP) method to iteratively improve an objective function by changing relative fishing rates, where each year/fleet block defines one parameter to be varied by the procedure, (e.g., setting four color code blocks means a 4-parameter nonlinear search). DFP runs the Ecosim model repeatedly while varying these parameters.

The parameter variation scheme used by DFP is known as a 'conjugate-gradient' method, which involves testing alternative parameter values so as to locally approximate the objective function as a

quadratic function of the parameter values, and using this approximation to make parameter update steps. It is one of the more efficient algorithms for complex and highly nonlinear optimization problems like the one of finding a best fishing pattern over time for a nonlinear dynamic model.

Nonlinear optimization methods like DFP can be tricky to use, and can give grossly misleading results. In particular the method can 'hang up on a local maximum', and can give extreme answers due to an inappropriate objective function. To check for false converge to local maxima, an option to use random starting F's should be used in addition to forcing additional iterations using the option to redo the analysis based on the current F's. To test for sensitivity of the results to objective function parameters, searches for a variety of values of the objective function weights and parameters should be accessed.

The objective function can be thought of as a 'multi-criterion objective', represented as a weighted sum of four criterion components or indicators: economic, social, legal, and ecological. Assigning alternative weights to these components is a way to see how they conflict or tradeoff with one another in terms of policy choice. For example:

- (a) placing a high weight on the net economic value component (total fishing profits) typically causes the optimization to favor lower fleet sizes and severe simplification of the simulated ecosystem to maximize production of only those species that are most profitable to harvest;
- (b) placing a high weight on the employment (social) indicator typically results in favoring larger fleet sizes, and again often severe ecological simplification in order to maximize production for the fleet that employs the most people.

External pressure, (e.g. in form of legal decisions) may force policy makers to concentrate on preserving or rebuilding the population of a given species in a given area. In Ecosim, this corresponds to setting a threshold biomass (relative to the biomass in Ecopath) and identifying the fleet structure that will ensure this objective. The implication of this policy tends to be case-specific, and to depend on the trophic role of the group whose biomass is to be rebuilt.

The ecosystem criterion component is inspired by the work of E.P. Odum (1971) in terms of 'maturity,' wherein mature ecosystems are dominated by large, long-lived organisms. This is implemented in Ecosim by identifying the fleet structure that

maximizes the biomass of long-lived organisms, as defined by the inverse of their production/biomass ratios. The optimization of ecosystem 'health' optimization often implies phasing out of all fisheries except those targeting species with low weighting factors.

The search procedure results in what control systems analysts call an 'open loop policy', i.e. a prescription for what to do at different future times without reference to what the system actually ends up doing along the way to those times. It would obviously be crazy to just apply an open loop policy blindly over time, each year committing a fishery to fishing rates calculated at some past time from only the data available as of that time.

In practice, actual management needs to be implemented using 'feedback policies' where harvest goals are adjusted over time as new information becomes available and in response to unpredicted ecological changes due to environmental factors. But this need for feedback in application does not mean that open loop policy calculations are useless: rather, we see the open loop calculations as being done regularly over time as new information becomes available, to keep providing a general blueprint (or directional guidance) for where the system can/should be heading. Also, we can often gain valuable insight about the functional form of better feedback policies, (how to relate harvest rates to changes in abundance as these changes occur) by examining how the open loop fishing rates vary with changes in abundance, especially when the open loop calculations are done with Ecosim 'time forcing' to represent possible changes in environmental conditions and productivity in the future. For an example of this approach to design of policies for dealing with decadal-scale variation in ocean productivity for single species management, see Walters and Parma (1996).

Maximizing Risk-averse Log Utility for Economic and Existence Values

One option in the search procedure for optimum fishing patterns is to search for relative fleet sizes that would maximize a utility function of the form $w_1 \cdot \log(\text{NPV}) + w_2 \cdot S \cdot \log(B) - w_3 \cdot V$, where the w_i 's are utility weights chosen by the user, and the utility components NPV, $S \cdot \log(B)$, and V are defined as:

- (1) NPV is net present economic value of harvests, calculated as discounted sum over all fleets and times of catches times prices minus costs of fishing, i.e., the discounted total profit from fishing the ecosystem.

- (2) $S \cdot \log(B)$ is an existence value index for all components of the ecosystem over time. It is calculated as the discounted sum over times and biomass pools of user-entered structure weights times logs of biomasses, scaled to per-time and per-pool by dividing the sum by the number of simulation years and number of living biomass pools.
- (3) V is a variance measure for the prediction of $\log(NPV) + S \cdot \log(B)$. It is assumed to be proportional to how severely the ecosystem is disturbed away from the Ecopath base state, where disturbance is measured at each time in the simulation by the multidimensional distance of the ecosystem biomass state from the Ecopath base state. This term is negative, implying that increased uncertainty about the predictions for more severe disturbances causes a decrease in the mean of $\log(NPV)$. The term represents both aversion to management portfolio choices that have high variance in predicted returns, and the observation that the mean of the log of a random variable ($NPV \cdot PB$) is approximately equal to the log of the mean of that variable minus $\frac{1}{2}$ the variance of the variable. Large w_3 -values can be used to represent both high uncertainty about predictions that involve large deviations of biomass from the Ecopath base state, and strong risk aversion to policy choices that have high uncertainty.

This utility function combines several basic concepts of utility. First, the log scaling of value components represents the notion of “diminishing returns”, that adding some amount to any value measure is less important when the value measure is already large than it is when the value measure is small. Second, the log scaling also represents the notion of “balance”, that no value component should be ignored entirely (unless it is assigned a zero w_i); the overall utility measure approaches minus infinity if either net economic performance (NPV) or if any biomass component of the ecosystem (any biomass B_i in $S \cdot \log(B)$) approaches zero. Third, it represents the notion that our predictions about the future of both economic performance and biodiversity (biomasses) become progressively more uncertain for policies that result in more extreme departures from the Ecopath base state about which we presume to have at least some knowledge.

In the terminology of portfolio selection theory in economics, fishing policies result in a portfolio of value components with “expected total returns on investment” equal to $NPV + S \cdot B$. But policies that have higher expected total returns are most often also ones that would push the ecosystem into more extreme states, and hence represent portfolio choices with higher variance in total returns.

For example, maximizing the deterministic prediction of NPV in Ecosim often involves a ‘farm-

ing policy’, in which fishing is deployed so as to severely simplify the ecosystem to maximize production of one or a few species that appear at present to be the most valuable (price, potential total catch). This may even involve deploying some fleets just to remove predators and competitors for the most valued species, just like deploying pesticides and herbicides to remove “pests” in agricultural systems. But simplifying an ecosystem in such ways can make the behavior of the system deeply unpredictable, by creating opportunities for ecological response (population growth) by a variety of species that are rare in the “normal” ecosystem, and hence are not well researched or understood in terms of their potential impacts on valued species should they become abundant.

Simplifying an ecosystem is hence much like investing in high-risk, high-return stock market options; such investments may make you rich, but they may also bankrupt you. Most people are risk-averse as investors, and seek to “spread risk” by investing in “balanced portfolios” with lower expected returns on investment but much lower probabilities of severe loss.

The prediction variance measure V is not meant to represent all components of variation or uncertainty about future biomasses and fishery values. V goes to zero for policies that hold or maintain the ecosystem at the Ecopath base state B_0 for every biomass, for all simulation times. It is obviously not correct to suggest that we would expect no variance in future biomasses (and hence in the harvest components of NPV as well) if such a policy were implemented. Imagine running a very large number of simulations of future biomass changes under such a policy, while varying all possible uncertain quantities such as the Ecopath base biomasses and biomass accumulation rates, productivities, Ecosim vulnerability parameters, environmental forcing inputs representing oceanographic productivity regimes, future demand and price patterns, and changing vulnerabilities to fishing due to biophysical and technological factors. Even for the baseline policy where Ecosim predicts stable (‘flat line trajectory’) expected or mean biomasses over time, these simulations would likely reveal high variances and complex covariance patterns for most biomasses over time, i.e. we would see wide probability distributions of possible future biomass states for the ecosystem. We should not be arrogant enough to suggest that we can describe all the uncertainties well enough to accurately calculate the variances of such distributions. But note that much of that variance in predictions of future biomasses, (and hence variance in the value components) would be due to sources of uncertainty

and variability that are the same no matter what the policy choice, i.e., would cause about the same amount of variance in predictions for any future harvest policy that we might simulate.

When comparing policy choices using an optimization objective function, there is no point in including extra constant terms that do not change with the policy variables, (e.g., a base variance V_0 in predictions that does not change with fishing rate policy and just represents uncertainty about any prediction that Ecosim might make). Hence the V distance measure is meant to represent only extra variance or uncertainty in predictions for policy scenarios that would likely drive biomasses far from the Ecopath mean state.

Note that Ecosim does not deliberately advocate or promote any particular risk-averse portfolio approach to public investment in ecosystem harvest and existence values. Rather, it provides the logarithmic utility function option so that users who do have highly risk-averse attitudes about ecosystem values can identify policy options that would better meet their objectives. Users should always construct a series of policy scenarios with varying utility weights w_1 , w_2 , and w_3 on the log utility components, to see how placing different emphases on these components would alter the predicted best policy choice.

Use of these functions for policy exploration will generally involve some balance between these objectives. Indeed, identifying the weighting factors to be given to each of these objectives may be the most valuable aspect of this Ecosim routine.

Thus, to assist the user in achieving this, the starting values of the objective functions have each been standardized relative to their base values (from Ecopath), making them roughly comparable. The first two of these measures tend to pull towards increasing fishing effort, while the two others tend to pull towards reducing effort. Care should be taken to consider this balance when giving relative weightings to the objectives. Also note that the optimizations should be performed with a range of weighting factors for each objective function, rather than with single values, which may miss a well-balanced solution (see *Cochrane, this volume*).

Open-loop Policy Simulations

The fishing policy search interface of EwE described above estimates time series of relative fleet sizes that maximize a multi-criterion objective function that includes net economic value, social employment value, mandated rebuilding,

and ecological stability criteria. In Ecosim, the relative fleet sizes are used to calculate relative fishing mortality rates by each fleet type, assuming the mix of fishing rates over biomass groups remains constant for each fleet type, (i.e. reducing a fleet type by some percentage results in the same percentage decrease in the fishing rates that it causes on all the groups that it catches). The fisheries and ecosystem may be simulated with Ecosim using the solution found in the policy search interface: this is termed an 'open loop' simulation.

Note that when density-dependent catchability effects are included in the simulations, reductions in biomass for a group may result in fishing rate remaining high despite reductions in total effort by any/all fleets that harvest it. Despite this caveat, the basic philosophy in the fishing policy search interface is that future management will be based on control of relative fishing efforts by fleet type, rather than on multispecies quota systems. It is in any case not yet clear that there is any way to implement multispecies quotas safely, without either using some arbitrary conservative rule like closing the fleet when it reaches the quota for the first (weakest) species taken, or alternatively allowing wasteful discarding of species once their quotas are reached.

If future multispecies management is indeed implemented by regulation of fleet fishing efforts so as to track time-varying fishing mortality rate targets as closely as possible, then a key practical issue is how to monitor changes in gear efficiency (catchability coefficients) so as to set effort limits each year that account for such changes in efficiency. Such monitoring is particularly important for fisheries that can show strong density-dependence in catchability, such that a unit of fishing effort takes a much higher proportion of some stocks (exerts a higher fishing mortality rate per unit of effort) when stock size(s) is/are small.

There are at least two possible ways to monitor the changes in catchability (gear efficiency) discussed above. Both are based on monitoring fishing mortality rates F_t over time, and using the relationship $q_t = F_t/f_t$, where q_t is fishing rate per unit effort and f_t is effort.

The first approach is to do traditional biomass stock assessments each year, and to estimate F_t as $F_t = C_t/B_t$, where C_t is total catch and B_t is estimated vulnerable stock biomass. The second approach is to directly monitor the fishing mortality rate, estimating probabilities of harvest using methods such as annual tagging experiments and within-year estimates of relative decrease in fish