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MULTI-SPECIES AND ECOSYSTEM MODELS

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ABSTRACT

The final decades of the twentieth century saw the emergence and first applications of multi-species models of marine ecosystems along with a general recognition of the potential importance of taking into account multi-species interactions when managing fisheries.

Multi-species effects can include biological and technical interactions. Technical interactions are frequently of concern, for example when discards of certain species are believed to be a consequence of the management system. Biological interactions may fundamentally change the perspective of how to utilise an ecosystem, since a fishery or a moratorium on a predator may completely change the survival of a prey and conversely, fishing on a prey may affect the growth of a predator.

Modern research on multi-species modelling is highly multidisciplinary in nature, drawing on expertise from fishery science, fish biology, ecology, hydrography, mathematics, statistics, economics, operations research and computer science. As the models become more detailed and complex, they are able to address more issues that are of concern to managers but at the same time it becomes ever more difficult to interpret results.

Fundamental issues are raised in the multi-species context, and particularly so when fishing is viewed in the light of the precautionary approach. Some multi-species research has indicated that heavier fishing with smaller mesh sizes may lead to more profits for the fishing industry, whereas most earlier single-species research has indicated that low fishing pressure, particularly on juveniles, would be beneficial for the resource and the fishery. Conclusions from other research have indicated that economic considerations such as maximum economic yield may not be applicable and have failed to lead to sustained utilization whereas the traditional view has been that long-term economic views will generally lead to sustainable use of the resources.

This paper seeks to resolve some of these apparent conflicts, drawing on the multidisciplinary nature of fishery science. It is seen that almost all points of view lead to the conclusion that fishing with low fishing pressure is not only sustainable but in accordance with the precautionary approach. Further, almost all multi-species concerns further strengthen the need for reduced fishing pressure.

It is also argued that simple management measures such as quotas, effort control or areal closures alone may not suffice to maintain viable fisheries in multi-species ecosystems.

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Introduction

[1] This paper endeavours to describe recent developments in multi-species modelling approaches and how the results from those developments will or are likely to affect management decisions. To this end, the sections following the introduction describe common current single-species methods of assessment and prediction, together with a description of multi-species issues that must be taken into account. Multi-species effects tend to be classified into two different types: biological and technical interactions. The paper discusses the importance of each of these effects, modelling approaches and how these effects affect the possible utilization of the resources.

[2] It turns out that quite a few important management questions can only be addressed through the use of quite complex models, which include several species, area and fine temporal scales. Such questions include the effects of closed areas, multi-species effects of a moratorium on fishing for a predator, and so on. Finally, given the current state of many of the world's commercial fisheries and problems recently found in management advice given in many regions, it seems clear that tools are needed to evaluate the ecosystems in a more comprehensive manner than previously.

[3] Models that include several species and their interactions have existed for quite some time, starting with the Lotka-Volterra models and later the emergence of models that can incorporate very many species. The first true applications of multi-species models of marine ecosystems were, however, seen closer to the end of the twentieth century (e.g. ICES, 1991).

[4] It has become obvious that in order to answer fairly standard management questions, the multi-species models need to be spatially dis-aggregated, and thus must contain a migration component in addition to the biological and technical interactions. These models are therefore much more complex internally than previous single-species models. The paper describes some of these issues, together with a related problem, that of using difficult and complex data sets to estimate unknown parameters of the models. When combined with prediction, the modelling approach requires a conglomerate of expertise from a variety of subject areas. This multidisciplinary nature of modern research on multi-species models is detailed in a separate section of this paper.

[5] Some fundamental issues are raised in the multi-species context, and particularly so when fishing is viewed in the light of the precautionary approach. In fact some conclusions appear to be in conflict and there is a need to resolve these conflicts in order to pave the way for reasonable management. Some of these conflicts can be resolved by drawing on the multidisciplinary nature of fishery science. Generally speaking, fishing with low fishing pressure is sustainable and in accordance with the precautionary approach. Most multi-species considerations further strengthen the need for reduced fishing pressure.

[6] Along with the application of the models comes a general recognition of the potential importance of taking into account multi-species interactions when managing fisheries. Thus, some of the first applications by advisory bodies immediately implied that some of the fundamental understanding of the effects of fisheries could, at least in principle, be seriously affected by multi-species considerations.

[7] A fundamental issue in managing marine resources is the overall level of fishing mortality to be exerted on the fish stock(s). The decisions on overall levels of harvest need to be based on all aspects of knowledge, first biological, but no less economic and social. Decisions on sensible fishing pressures paves the way for what control systems can be implemented, since they must be designed to achieve predefined goals.

[8] It will be seen that simple management measures such as quotas, effort control or areal closures alone will not in general suffice to maintain viable fisheries in multi-species ecosystems.

Rather, combinations of these measures are needed to safeguard against the various issues raised in the multi-species context.

The single-species models of assessment and prediction

[9] The simplest and most common single-species models include recruitment, growth, maturation and mortality due to fishing and natural causes. In their simplest, initial forms (Beverton and Holt, 1954) these models commonly assume constant natural mortality, constant growth, a constant maturation pattern by age and a constant fishing pattern by age.

[10] Initial analyses of the effects of fishing may use these simple assumptions in order to evaluate the likely development of a yearclass and its possible utilization. Even the simplest such analyses need to consider the effects of incorrect assumptions. These simple computations subsequently provide first indications of potential yield from the resource, but need some estimate of yearclass size as input.

[11] In order to obtain such typical yearclass sizes, some assessment of the resource is needed. Such assessment techniques vary. Classical methods include those which track individual yearclasses, initially VPA (Gulland, 1967) to more recent statistical methods that incorporate more appropriate statistical assumptions (but see below). Whatever the methods, the outcome will be some stock estimate, typically in terms of the historical number of fish by age and year, up through the last data year.

[12] In order to evaluate the effects of even the simplest management policies, the effects of these need to be modelled. Usually this is done by predicting the stock forward in time (i.e. from the assessment year), under the given harvest policy.

[13] In order to undertake predictions, some stock-recruitment relationship needs to be used. This can be estimated from data, assumed to be a constant or to be of some general form. It turns out that the stock-recruitment relationship is of crucial importance when estimating the sustainability of a harvest policy or probability of stock collapse.

[14] The natural next steps involve the addition of factors such as cannibalism and density-dependent growth, if any of these are believed to be important.

[15] These fairly simple methods have been used extensively to estimate longer-term consequences of management actions.

[16] Alternative approaches to assessments and predictions have been developed. These include aggregate models that require less data but also provide less output. Such simpler models are very useful in certain circumstances and may prove better than the more dis-aggregate models in some circumstances (Butterworth *et al.*, 1990). It is, however, clear that overly simple models cannot answer any of the more complicated issues in multi-species research.

[17] These model classes range from very simple static biomass production models, through dynamic total biomass models, to age-dis-aggregated dynamic stock production models. Unknown parameters (e.g. recruitment) in the last model class are usually estimated using statistical methods of fitting models to data (but see below). Although given different names, such as HITTER-FITTER (see e.g. Punt and Butterworth, 1991) or ADAPT (Gavaris, 1990), resulting techniques are all of the general form of adapting an internal model to data.

[18] All single-species assessment models considered here are of the form of an internal black-box, which simulates an ecosystem based on some parameters. Results from different parameter values are compared to data and the parameters are estimated by finding the best fit to the observed measurements.

[19] In order to estimate the various unknown parameters of the models, statistical methods are used. During most of the last century this step was skimmed over by using simple assumptions (such as independent log-normal errors), though in rare cases these were augmented by using

known statistical distributions believed to better describe the sampling process. However, subsequent analyses indicate that these assumptions are far from correct and that the sources of variation in the measurements are sufficiently complex to warrant the development of completely new statistical distributions to describe the data sets. This was noted early on for abundance data (Pennington, 1983; Stefansson, 1996), but for other biological data, such as length distributions, simpler assumptions have been used (McDonald and Pitcher, 1979), though in rare cases these have been extended to multinomial distributions (Methot, 1988). Recent research has indicated that these various extensions still suffer from being highly inadequate descriptions of reality (Hrafnkellsson and Stefansson, 2001).

[20] Although these statistical issues may seem esoteric, the results of incorrect statistical assumptions can, unfortunately, have devastating effects on overall conclusions. This is best seen by considering the best currently applied single-species assessment methods, which can not only provide stock estimates but can also estimate uncertainty. One way of describing the uncertainty is to provide intervals that describe probability. A statistical method will, for example, provide a biomass level below which it is highly unlikely that the true biomass can lie. In particular, such a 1% lower confidence bound is designed in such a fashion that the true biomass should only be below it in 1% of all assessments. The best illustration of the problem involved is that recent research has indicated that when the standard statistical assessment methods report a 1% lower bound on a biomass value, in reality the true probability of being below that value can easily be 30%, and the most commonly used assessment methods give a corresponding underestimate of uncertainty (Gavaris *et al*., 2000; Patterson *et al*., 2000; Restrepo *et al*., 2000).

[21] The result of the statistical issues above is that even if management has been aiming for a low fishing mortality, to be 99% certain of the stock staying above a depletion level, the actual probability may have been 30% of falling below that critical point (Gavaris *et al*., 2000).

[22] For predictions it is essential to take into account the high degree of uncertainty involved in predictions of the development of marine species. Most management bodies need to know not only immediate and future yields but also probability of stock collapse, inter-annual variation in yield, likely rebuilding time, etc. The fact that recent work in this area has indicated that previous estimates of uncertainty may have been severely underestimated and that new and sophisticated statistical methods are required raises serious issues of reliability of predictions in general.

[23] In spite of their problems, single-species models have provided guidance on methods for rational utilization of fish stocks. In a nutshell, general results from these models are the following:

- A low fishing mortality will generally decrease the probability of stock collapse.
- Low-to-medium fishing mortalities will not usually lead to reduced harvests.
- High fishing mortalities may lead to reduced harvests.
- High fishing mortality may lead to stock collapse.
- Economic considerations tend to imply a need for even lower fishing mortality than implied by biological models alone.

[24] These results may not be completely universal conclusions from all single species models, but very nearly so. These resulting points of view will be termed the single species *basic premises* as they have resulted in fundaments used in fisheries management worldwide.

[25] This is not meant to imply that the single species models are correct or provide an adequate description of the ecosystem, but merely that the tenet of a low fishing mortality appears to hold as more complex situations are analysed.

[26] Apparently, in many cases, the broad results of severe management actions have been predicted adequately using fairly simple models. Thus, for example, a number of stocks have

shown reduced total mortality during reduced fishing pressure and have even regained earlier levels following such management action (e.g. herring, Jakobsson, 1980). This is not true in all cases however, as in some cases mortality does not appear to decrease following a stock collapse, even if fishing is reduced to a moratorium.

Multi-species effects

[27] Although there are several examples of fisheries which can be classified simply as cases of overfishing and the importance of reducing fishing intensity is clear, there are quite a number of instances where the questions raised are somewhat more complex than these. Simple examples of questions such as the predicted effects of a closed area or the effect of an increase in a predator stock on its prey involve a necessary deviation from the simple models. It is simply not enough, for many (if not most) purposes, to have simple eye-glasses. Rather, the analyses and interpretations must take into account the fact that species do not live in isolation.

Biological interactions

[28] In order to model multi-species effects, it is necessary first to develop a list of effects that may be important. This is the difficult step in modelling, as the mathematical and statistical models will follow naturally once a conceptual biological model has been developed.

[29] Following the single-species models in the previous section, the next natural steps in model extensions involve the biological interactions between species. Typically, these interactions involve predation and the resulting primary effect of predation on the mortality of the prey (Helgason and Gislason, 1979). The second factor to be taken into account is the effect of the predation on the growth of the predator. Depending on the ecosystem, one or both factors may be important (ICES, 1991).

[30] As for single-species models, approaches to the multi-species models vary from simple model extensions through holistic approaches where the main processes in the system are cast in a unified mathematical framework. Even in the holistic approach, however, there is considerable scope for choice, ranging from the very simple ECOPATH approach (Christenesen and Pauly, 1990), which starts as a simple equilibrium biomass flow model, through models such as MSVPA, which are dynamic and age dis-aggregated for all (or most) species.

[31] These first models are useful in determining the main multi-species effects in the systems. In particular, ECOPATH is designed to indicate whether most important players in the system are included and MSVPA will similarly indicate the most important sources of predation mortality for each species.

[32] Although in principle spatial factors may be important even when just considering one species, these factors become crucial when biological interactions are considered. The reason for this is of course the question of spatial overlap between the predator and prey species, which has been demonstrated in many ecosystems to be highly variable, resulting in widely varying predation mortality (e.g. Bogstad *et al.*, 1994; Bogstad and Tjelmeland, 1990). The decision to take spatial variation into account has several important consequences, the obvious one being the development of a more realistic model. Other consequences include a much more complex model. Migration typically depends on the maturity stage of the fish, thus further implying that the model must take into account the difference in behaviour of mature and immature fish.

[33] In variable ecosystems where some species are tightly coupled with a predator-prey relationship of considerable importance for both species, it therefore becomes important to incorporate fishing, predation mortality, growth as dependent on consumption, maturation and migration (Stefansson and Palsson, 1998).

[34] These models include a large number of parameters, values of which can only be estimated using statistical techniques. Although in principle standard statistical methods can be used, fisheries data are very difficult to handle and highly specialized methods are required.

[35] Although it will not be known in advance how complex the models need to be, it is clear that testing the effects of complexity can only be done using highly detailed models. A possible conclusion from such model tests may be that the complexity is not needed in the models, but this cannot be known in advance. Recent work has indicated that highly complex models can indeed be evaluated and tested using advanced statistical techniques (Helu *et al*., 2000).

Technical interactions

[36] Technical interactions are frequently of concern, such as when discards of certain species are believed to be a consequence of the management system. Further, different components of a fleet may target different components of a stock, most notably some components of the fishery may target the spawning stock in a spawning area during spawning time whereas another part of the fishery may target smaller juvenile fish.

[37] For this reason, when technical interactions are concerned, the need quickly arises to take into account fine temporal and spatial scales.

[38] In terms of modelling, few issues or added complexity tend arise due to the inclusion of technical interactions. In contrast, if fleet behaviour is added as a model component, together with the fleet’s response to economic issues, then a considerably different emphasis may develop (Olafsson *et al*., 1991).

Model complexity

[39] As mathematical models become more complex, there is increased potential for serious issues of confounding to appear. The net effects of such confounding can become quite serious. One of the simplest forms of such confounding appears in disputes over whether mortality is mainly due to fishing or natural causes.

[40] These simple confounding issues and resulting debates can in many cases be easily resolved. In most sciences it is standard practice to use designed experiments to verify what models are incorrect. Contrary to popular belief, large-scale experiments are also common in fisheries, although rarely designed explicitly to answer specific questions. Examples of such experiments include complete closures of fisheries due to stock collapses or wars, and implementations of strict management measures based on model predictions. Such experiments have repeatedly demonstrated that the basic premises of single-species fish population dynamics as mentioned earlier are fundamentally correct.

[41] It is of course exceedingly useful to have such experimental results that verify model predictions. In more complicated models, the confounding between factors can be of such a nature that it is impossible, using current methods, to verify true relationships.

Multi-species modelling approaches

[42] Modern research on multi-species modelling is highly multidisciplinary in nature, drawing on expertise from fishery science, fish biology, ecology, hydrography, mathematics, statistics, economics, operations research and computer science. Naturally, the more extensive the inclusion of such factors, the more complex the models.

[43] It must be noted, however, that some of the most important conclusions regarding fisheries and overfishing do not depend on complex models. In particular, some particularly simple techniques can be used to demonstrate serious overfishing. If the sole purpose of analysis is to find such effects, then there is often no need to go into excessively complex models.

[44] In some cases, relatively simple extensions to single species models can be used to verify effects of individual multi-species interactions. Thus the effect of a predator or a prey species can sometimes be entered as a simple regression variable (Pope and Knights, 1982; Stefansson *et al*., 1998).

[45] When developing models of the highly complex type considered here, the first step needs to be to define the biological factors to be taken into account. Having done this, the next step involves defining the corresponding mathematical model of the processes involved, followed by implementing the models using computer programming.

[46] The statistical aspects of the models become even more important in the multi-species models than in the single-species case. This is due to the increase in the number of data sets that must be used. In the single-species case, these will be only a few data sets, but even there the weight given to each data set may be quite important. In the multi-species case, a combination of either incorrect weights or inappropriate statistical assumptions may completely invalidate the output from the models (Stefansson, 1998).

[47] Having obtained the basic framework, the most promising current direction appears to be to build models of increasing complexity by comparing them to data in a stepwise fashion (Helu *et al*., 2000). This does, however, require appropriate statistical assumptions. Some of the current modelling work attempts to address all of these issues (Anon, 2001).

[48] Economic considerations must be taken into account if it is of interest to compare different fishing strategies, since they may lead to a shift in catches from one species to another and thus the regimes can only be compared using costs and income rather than simple biological yield. When attempting to find optimal harvest strategies or only to compare different strategies, methods of operations research, including maximization of utility functions, or at least comparisons of utility, are commonly used (Danielsson *et al*., 1997).

The precautionary approach in the multi-species context

[49] Traditional economic analysis would imply that fishing should be in such a manner as to ensure maximum long-term profits (or, more generally, maximum utility). Depending on what factors are taken into account, this has sometimes been simplified to maximizing total yield of a species in the long term, leading to maximum sustainable yield (MSY), corresponding fishing mortality (F_{MSY}) or other biological measures (e.g. $F_{0.1}$), which do not take economic considerations directly into account but aim for effort slightly lower than that giving maximum yield, as would happen if a cost function were used.

[50] The fundaments of these approaches have come under considerable fire in recent years, particularly due to the (near-) collapse of many fish stocks (Mangel *et al.*, 1996). It is, however, clear that most of the major stock collapses have occurred due to a combination of several factors, one or more of which led to considerable overfishing, i.e. fishing from most collapsed stocks simply was not in accordance with MSY or any other similar criterion.

[51] This does not alleviate the problem, however. The fact remains that stocks collapse and do so even when official policy is to maintain moderate harvests from the stocks. The reasons are usually not a policy of overfishing or a policy of fishing over MSY (there are of course exceptions where management directly aims for high fishing mortality, but these will not be addressed here). Rather, the official policies tend to be of moderate fishing, but the problem becomes one of a failure to attain this goal. The question becomes how to revise policy in order to ensure that harvests are sustainable despite the considerable uncertainty involved both in the science and in the implementation. In particular, it would usually be quite adequate to maintain a policy of MSY as a target, if it could be ensured that this would rarely be exceeded.

[52] In order to suggest remedies, it is of some importance to recognize a few causes rather than just the symptoms. Direct and documented causes of stock collapse or problems (serious and unexpected declines) include the following: incorrect advice on stock status; fishing well over advised levels; and lack of advice on danger levels and multi-species or environmental effects.

[53] The precautionary approach, stated in its simplest form, implies that care needs to be taken to ensure that fishing is undertaken in a sustainable manner and that when uncertainty is present,

this should be taken into account by reducing fishing mortality. In implementing the precautionary approach, reference points have been defined. Loosely, they are defined in order to set rules that satisfy the criterion that as long as fishing is within bounds defined by the reference points, fishing mortality will not exceed specified harvest rates.

[54] Now, considering the present framework, these things become a bit more complicated. The easiest example involves a prey species that has been reduced to a very low level. Overfishing a predator species may then re-instate the prey to previous levels much faster than any other measure, but this would clearly violate the precautionary approach as regards the predator. At present there is no system in place to address issues such as this.

[55] Some multi-species research has indicated that heavier fishing with smaller mesh sizes may lead to more profits for the fishing industry, whereas most earlier single-species research has indicated that low fishing pressure, particularly on juveniles, would be beneficial for the resource and the fishery (ICES, 1991). It is indeed easy to envisage how this could happen, simply through a reduction in the abundance of juveniles of a predator. This particular scenario serves as a good case study for how results must be interpreted when viewing through the precautionary looking-glass.

[56] These results were obtained from simple forward projections that included some multi-species interactions. It is not enough to have slight indications of such results, since there is considerable information to the effect that heavy fishing on juveniles can dramatically increase the probability of stock collapse. As a result, the jury is still out on what the net effect of such changes would be in the long term. Clear results, however, include the effect of heavy fishing quickly drawing stocks to stock collapse and of no fishing, in which case species can survive for millions of years. It would seem, therefore, that very strong evidence indeed is required to conclude that high fishing mortality of juveniles is beneficial.

[57] In examples where economic concerns have been included, case studies exist where it is predicted that the result of reducing fishing mortality on a predator will lead to more than 50% reduction in catches of a prey (Danielsson *et al*., 1997). In that particular case, economic analyses indicated that it was nonetheless beneficial to the fishing industry to accept those reductions since the predicted total profits more than outweighed the negative aspects. Interestingly, in this case the prey species did indeed collapse subsequent to an increase in the predator biomass.

Management in the multi-species context

[58] Initially, the inclusion of multi-species interactions, technical interactions, advanced mathematical and statistical models leads to considerable obfuscation. Thus, it is no longer uniformly clear whether mesh sizes should be increased or reduced, or whether fishing pressure needs to be reduced or increased to obtain sustainable fishing mortality.

[59] Upon some reflection, however, it is clear that the emerging figure is not as muddy as might appear at first. It must be noted at the outset that decisions on utilization should always take note of the precautionary approach. This implies that any uncertainty needs to be interpreted in favour of reduced fishing pressure. Thus, the fact that some new issues and questions are raised has no effect at all on principles such as a need to maintain low fishing mortality. Until clearly understood, such issues and questions merely urge more caution than before.

[60] Most multi-species and technical interactions lead to conclusions that further emphasize the need for low fishing mortality.

- Results that indicate that fluctuations in a predator species may have adverse effects on survival of a prey imply that fishing effort on the prey must be reduced even further than previously thought.
- Results that indicate that the growth of a predator is positively influenced by the growth of a prey will imply that more care needs to be exercised in the prey harvest than before.

- Estimates of uncertainty will tend to be higher (and better) since more factors are included than before, leading to more aversion from high fishing mortality.

[61] Multi-species results of a different nature include:

- In a 3-species system, reduced pressure on a top predator may adversely affect its immediate prey, an intermediate-level species. This species may have its own prey (or competitor), which will become successful due to the reduced predation (or competition) pressure. Examples of such systems appear to exist (Bogstad *et al.*, 1992).
- Effects of predation on stock-recruit relationships of prey appear to be very complex and the resulting effects on, for example, biological reference points are even more difficult to interpret (Gislason, 1999).
- Some examples of multi-species results also exist where predicted effects of mesh changes contradict earlier single-species results (ICES, 1991).

[62] Finally, there are instances where a species may suffer (almost) total mortality after spawning (Vilhjalmsson, 1994). In these cases, there is considerable incentive to fish up the stock before natural mortality occurs. In a few cases, a holistic approach has been taken, i.e. considerations of the effect of prey biomass on predator growth have been taken into account. In such situations, it has sometimes been found that the lack of catches of the prey species is offset by an increase in the growth of the predator, even to the extent of matching the loss. In the spatially explicit multi-species context, these factors crystallize even further, since it is clear that some of the dying prey will provide food for the predator. There is, therefore, even less incentive to fish hard on the prey. The full results of such analyses depend, however, on the economic importance of each of predator and prey. Such predator-prey price ratios may differ greatly from one ecosystem to another (e.g. the different price of anchovy compared to capelin).

[63] It is seen that there may indeed be examples where the inclusion of multi-species effects implies that fishing pressure should be increased in order to obtain higher yields and even to obtain a more stable or sustainable fishery. As these finding appear to be exceptions, what remains, however, is the need to demonstrate this in individual situations. It is therefore not a valid argument to point to these exceptions and argue that this justifies increases fishing mortality. Such justification must be clearly demonstrated based on data and models for the given situation. The default methodology under the precautionary approach needs to be the prudent one of low fishing pressure since this appears to be the general situation. This conclusion is even more important in the light of results that imply that simple control rules that ensure low fishing mortality will perform well even in situations of considerable variation in the true biological parameters of the populations (Walters and Parma, 1996).

[64] Thus, lack of knowledge of interactions simply qualifies as any other reduced knowledge and implies a need for low fishing mortality. The reduced fishing mortality is unlikely to lead to a lack of total catches from the system.

A missing component in the models

[65] Notably absent from most if not all current single- and multi-species biological and economic models is the concept of maximum potential effort. In a system with some form of limited entry this can be very different from the effort as intended by management. Basically, in a system with limited entry there is a possibility of an enormous dormant effort.

[66] The inclusion of such a concept would immediately bring forward the following model components, which are currently not implemented in models of marine ecosystems:

(i) A large dormant effort results in a constant political pressure to increase realized effort. A model to take this into account should place a probability of a political decision to increase fishing mortality over a sustainable threshold, simply due to political pressure. This applies to all control systems.

(ii) At any given point in time, an increase in Total Allowable Catch (TAC) or effort allocation can always be realized, even if this is erroneous and leads to a major increase in fishing mortality. This applies not only to TAC and effort control systems but also to systems based on areal closures (the effect of an areal closure may thus be negated by a large fleet fishing in adjacent areas).

(iii) An estimation error towards a low TAC (or effort) is unlikely to be realized as a low death rate symmetric to an overestimate. In addition to the political pressure, this is also a result of high grading, discarding of the species that will occur with other species that have not been underestimated, and an unknown slippage mortality due to excessive fishing activity on other species or size groups.

(iv) For a small fleet size, the effect of quota variation and discordance among species is negligible since the individual vessels will not be able to catch species that are not abundant. Basically this is due to the maximum possible excess effort in a small fleet. Thus there is a built-in guard against overfishing simply in the fleet size. With excessive dormant effort, however, vessels will find ways to fill all quotas, resulting in all overpredictions directly realized in mortality and excessive slippage in other species.

(v) An oversized fleet can subsidize the fishery of certain overfished species through the catch of a more abundant species. This can happen, for example, when the fishery for a depleted species cannot economically sustain individual fishing trips and a more abundant species justifies the trips and sailing time, but the catches of the depleted species can be taken at minimal additional costs during the trip. This only occurs as a consequence of the combination of multi-species issues and oversized fleet.

The potential effects of dormant capacity become particularly clear in light of multi-species or (biological or technical) interactions. It would therefore seem clear that the basic concept of dormant capacity is important enough to warrant inclusion in multi-species models. It is equally clear that this issue needs to be addressed by management.

Control systems in the multi-species context

[67] Management systems typically depend on one or more of quotas, effort control, areal closures, or other technical measures, such as mesh size changes. Considerable scientific and empirical evidence has been provided for the performance of each of these systems. These control mechanisms can now be viewed in the light of knowledge gained from the development of the multi-species models. Some problems affect all of these system, most notably problems of discards or high grading and catchability variation.

[68] High grading can be a general problem, particularly at high catch rates. Regardless of the control system chosen, it is economically viable for a vessel crew to decide to discard low-value fish for high-value catches under any limitation whatsoever. In particular, the limit put by the size of the hold in the vessel is enough to warrant discards under high catch rates. It can be beneficial to the operations of a freezing trawler to discard an entire hold full of frozen fillets if they are of a low-enough value species, should the vessel find a spot with another species of high enough value. This can occur under any control system (including free fishing).

[69] Environmental changes can result in considerable changes in catchability which, when not taken into account, will lead to incorrect predictions (Stefansson and Eiriksson, 1998). These variations have an effect on the uncertainty of estimates of stock sizes and thus on appropriate effort, size of areal closure or TAC, thus affecting all control systems.

[70] A few examples suffice to show that each of these systems, when implemented alone. suffers from deficiencies.

Failure of a well-designed quota system

[71] Quota (or TAC) systems are based on deciding an annual TAC for each species. A well-designed quota system is one where the catches taken are in accordance with the quota set, which again is according to some system that aims to provide sustainable catches for the species involved. In principle, a quota system should not need to include other issues such as effort control or fleet size regulation, since the primary issue of fishing mortality is addressed directly by setting the TAC to achieve a pre-specified goal.

[72] A quota system can thus in principle limit fishing mortality inflicted on a given species. Without any further limitations, however, a fleet can move its effort towards areas of high abundance of spawning fish or of high abundance of juveniles. Such an increased effort towards certain age groups can easily lead to very high fishing mortality on certain age groups. The following model is an example where an initial design of a quota system will fail badly through perturbations not covered by the quota system.

[73] Suppose the quotas are intended to be set so that the TAC appropriate for each species is according to a sustainable fishing mortality. Several of the following problems have been recorded with such a set up, whereas others are plausible explanations for existing situations:

(i) Uncertainty in the estimate of the fishing mortality may give a considerable (e.g. 30% overestimate of the desired quota of some species, resulting in increase in fishing mortality from the target. These effects tend to become hangover effects for several years, exacerbating the situation (Rivard and Foy, 1987). The true uncertainty in the population estimates has only recently been investigated (Gavaris *et al*., 2000).

(ii) Re-allocation of effort between areas can change the fishing pattern for a given species so that the juvenile or other component gets twice the intended effort, leading to high probability of stock collapse (Rose, 1993). This problem is not addressed in models unless spatial effects are modelled directly.

(iii) A species whose stock size has been overestimated can get a quota which is so high that it is virtually impossible to catch, leading to serious difficulties in a fleet which searches for this target species but catches only other species whose quota has already been taken. The net result can be a serious discard problem.

(iv) A species whose stock size has been underestimated may get discarded since it appears much more frequently in the catches than predicted.

(v) A species with very low tolerance to fishing can be overfished even when taken only (or mainly) as by-catch in a fishery for another species that is sustainably fished (Walker and Hislop). This is an important example of a multi-species effect not normally taken into account when a TAC system is designed.

[74] It is seen that, from a modelling and advisory point of view, there are problems involved in evaluating the effects of management actions in a TAC system, problems that are not addressed using the models in common use around the world. In order to evaluate these effects new and more complex models are needed, taking into account spatial effects, multi-species effects and different statistical design.

[75] It is thus seen that from an implementational point of view that there are several issues which may not be addressed in any detail within a quota system. In particular, a quota system based on TAC allocations for individual species may not lead to a sustainable fishery for all species involved, even the target species.

Failure of a well-designed effort-control system

[76] An effort-control system is defined by some measures designed to limit the total effort that a fleet can exert. A well-designed system will attain the effort limitation intended and the intended effort level corresponds to some sustainable fishing mortality for certain target species under a given scenario.

[77] The primary problem with this method is that the fleet is free to target its effort to any species, species group or size classes within the system. The total effort reduction will typically be set to be adequate to harvest the system according to a sustainable fishing mortality under a specified harvest regime. In most fisheries this implies that the fleet has been fishing in several areas and on several species. The effort system should lead to sustainable use of the resource if there are no changes in how the fleet proportionally targets each part of the species complex.

[78] This design completely missed the multi-species viewpoints and spatial variation in species or age composition.

[79] The net effect of this omission can be arbitrarily devastating. In the simplest example, the fleet consists of two discrete components, each of which fish for its own target species. In the typical scenario, the effort controls are designed to bring fishing mortality down to just below a collapse fishing mortality level, but in the best of worlds the target may be about half of the collapse mortality. In either case, if the price of one species increases sufficiently, the two fleets will both go for that species, leading to stock collapse. Given the first collapse, the fleets will target the second species.

[80] A price change is not even needed for this to happen. Natural variation in stock size will usually be sufficient for a behavioural change in fleet behaviour. Thus, if the size of one stock goes sufficiently down due to natural variation, the fleet will target another species.

[81] Finally, in no known cases of effort limitations has any attempt been made to account for the increase in catchability inherent in most fleets.

[82] Examples are available of long-term catchability increases of 4.7% per year (Stefansson, 1998). It must be considered highly likely that in an effort control system the incentive for increasing efficiency and thus catchability would be even greater than this. In such a system, with limitations on the total number of fishing days, the number of days allowed per year would therefore need to be reduced by **a minimum of 10% per year every year** simply to ensure that fishing mortality would not be guaranteed to increase steadily.

[83] Interestingly, this even happens for the smallest vessel classes, sometimes term artisanal vessels or owner-operated vessels, typically with 1-2 crew members. Thus, there are examples of owner-operated vessels with 4 computerized winches and GPS positioning equipment. No formal estimates of catchability exist in this case, but from total catch figures it is clear that it is possible to maintain considerable catches with such configurations.

[84] In some countries, these vessel classes tend to receive different treatment from the rest of the fishing fleet. Unfortunately the catches have exactly the same effect on fishing mortality, regardless of the political status of the fishery.

[85] It is seen that the usual single-area, single-species models of assessment do not take into account the likely variation due to species switching or spatial re-allocation within an effort-control system. Advice based on these models is therefore unlikely to capture much of the variation due to the system itself.

[86] In addition to the advisory problem, a pure effort-limitation system does not in general guarantee conservation of fish stocks in any sense. It is, however, clear that reducing effort to zero will work. It follows that the only way in which effort limitations will work is if the limitations are such the fleet can not induce high fishing mortality even with complete re-targeting

of total potential effort, **and** the effort is further reduced every year to account for possible efficiency increase.

Failure of a well-designed areal closure

[87] Areal closures are designed to protect a certain collection of stock components. A well-defined areal closure succeeds in eliminating fishing from the area in question.

[88] Areal closures are sometimes temporary closures of small areas. These clearly will have little effect in a general overfishing situation. Similarly, closures that are only temporary (e.g. short seasonal closures) cannot provide any guarantee against overfishing, which can take place in other areas at other times. For example, common closures of spawning grounds during spawning time provide little protection for spawning fish since the spawning stock can be reduced to arbitrarily small levels through fishing on immature fish or on mature fish before the spawning season. The net effect of fishing 50% of a yearclass before it matures is exactly the same as fishing 50% of the yearclass on the spawning grounds as the yearclass is preparing to spawn for the first time.

[89] Closures of major portions of the fishing grounds have, on the other hand, apparently been seen to considerably affect fishing mortality (Murawski *et al.,* 2000).

[90] Some existing closures of juvenile areas are also likely to have an effect on the survival of juveniles (e.g. Vilhjalmsson, 1994) and thus on the survival of the stock (Myers and Mertz, 1998), but this does not seem to have been demonstrated through any evaluations of the effects of such closures.

[91] In general, this may not hold, however. Suppose an areal closure is implemented in order to protect a given species. The simplest example where this will not suffice consists of a single species which has a migration pattern between certain areas, one of which is taken to be the closed area.

[92] The crucial factors in determining the effect of a permanent areal closure will be the rate of emigration from the area and the fishing mortality outside the area. This is because, if no other restrictions are implemented, then there is no intrinsic upper bound on the fishing mortality that can be implemented outside the closed area. Thus, the only upper bound on mortality due to fishing is simply the emigration rate. If the closed area is increased, the emigration rate is reduced and in the limit the areal closure will provide full protection.

[93] In some situations knowledge may be available about the migration rate and it may also be possible to estimate fishing mortality with reasonable reliability. In these cases, it is in principle possible to estimate the effects of the areal closure. It is clear that such computations are essential if areal closures are to be generally useful as management tools. This implies a need for models that incorporate explicitly migration and provide estimates not only of the effect of fishing in the open areas but also of the associated uncertainty.

[94] In cases when such data are not available, it is very difficult to make any sensible statements as to the effect of areal closures except of a generalist type. In particular, it is clear that there are many scenarios where unlimited fishing activity outside a closed area may lead to stock collapse. This will certainly be possible under several known migration patterns. Examples include such diverse species as tuna and cod.

[95] Thus it is seen that current single-area assessment models do little to predict the effects of an areal closure and, in the usual absence of scientific data on migration rates (including their uncertainty), it is not possible to provide advice on the net effect of these closures. Calling such areas sanctuaries does not in any way change the basic problem that the full effect of these on the population dynamics and sustainability is unknown and will in some cases be negligible.

[96] It follows that the only situation when there is any sort of guarantee that an areal closure suffices to provide sustainability for a stock is when the area is so large that most of the stock is protected.

Failures of other technical measures

[97] Other technical measures tend to be aimed at protecting certain age groups, length classes or maturity stages. Typically, these involve mesh size increases or other changes in fishing gear.

[98] If the technical measures are not combined in any way with overall fishing mortality limitations, then fleet development can continue to increase total fishing mortality without any specified upper limit. Thus, in general, the technical measures cannot be expected to guarantee a sustainable fishery.

[99] The multi-species effects of, for instance, mesh size changes are quite contradictory. Some available research indicates that mesh increases thought to be beneficial in a single-species scenario may lead to reduced catches in a multi-species scenario. These results have to date not taken into account spatial variation in species composition, which is in some cases known to completely change the outcome of the models.

[100] The only instance when technical measures alone can be expected to provide a sustainable fishery is when they result in a complete termination of fishing on juvenile fish (Myers and Mertz, 1998). Even in this case, however, the mortality due to slipping through meshes is completely unknown. The mortality due to slipping through meshes may be arbitrarily high unless some other measure is included to reduce total fishing mortality. Slipping mortality is not included in any standard assessment models.

[101] It can therefore be seen that these technical measures are unlikely to be sufficient in general to provide a sustainable fishery. It can be further seen that the state of the art in population dynamics models is unable to provide adequate advice on the (multi-species) effects of these technical measures.

Combined control systems

[102] It is seen that unless there is substantial quantitative evidence to the contrary, the usual control measures are not guaranteed to control fishing mortality and lead to sustainability. Some combinations are more likely than others to work, however.

- A combination of a TAC system with effort controls should reduce both the multi-species problem of re-allocation of effort between species (under effort-only control) and multi-species discard issue in the mis-specified TAC in the TAC system.
- A combination of major closed areas for juveniles combined with a TAC system should reduce the (single-species) problems of fishing to unsustainable levels either due to re-allocation of effort to juveniles or overfishing in the open areas.
- A formal fleet reduction system in combination with any known control system will reduce all problems with every system. As with effort controls, however, a fleet reduction system is not enough on its own.
- An effort control system along with large areal closures is much more likely to provide sustainable utilization than either system alone, since the combination can both provide a refuge and ensure that total effort is limited outside the closed area.

[103] Any of these combinations would have to be designed in such a manner as to aim for an adequate definition of each component. Naturally there would be no use in adding an effort system to anything else, unless the effort control was designed to truly control effort to sustainable levels.

[104] The implementation of such combined systems is outside the scope of the present paper. It is, however, clear that such combinations are quite possible, though they may become somewhat complex. For example, an effort control system can in principle easily be added onto a quota system with individually transferable quotas. Initially, this could be done by allocating each vessel its historical effort, subsequently allowing transfer of effort between vessels and reducing effort year-by-year sufficiently to guarantee more than compensation of efficiency increase. Naturally, effort of large vessels needs to count more than the effort of small vessels in such a system, but the precise numbers are largely irrelevant in order to see some of the benefits of the combination.

[105] As seen earlier, all of the systems are likely to fail in the case of dormant effort in the fleet. The usual exclusion of this effort from models leads directly to a bias in the predicted effects of all management action. Including multi-species and technical interactions in the prediction models may possibly alleviate the assessment problem somewhat but will not eliminate it completely. No current models are able to take into account the full potential effects of the overcapacity currently available in many of the world’s fisheries.

Conclusions

[106] The paper has indicated the directions which current multi-species models have taken, how they have been developed in attempts to answer some of the questions raised by management and take into account various important biological issues. In terms of the utilization of resources, it is seen that the basic premises of classical single-species analyses hold in most instances, namely that maintaining low fishing pressure remains a prudent policy, is in accordance with the precautionary approach, is likely to provide sustainable catches, and will result in good yields in the long term. However, concerns raised in modern statistical, spatial and multi-species models indicate that the maintenance of low fishing pressure is much more difficult than previously believed. This is due to a combination of many factors, from management issues in the multi-species context. through estimation problems due to biological and statistical issues raised in complex models of ecosystems. As a result, there is a much greater need to further reduce fishing mortality than ever considered previously.

[107] It is seen that when these more complex models are developed, several practical issues arise in the interpretation of results, as well as in the development of the models. There are at present fundamental unsolved issues in the very model definitions (not to mention implementation in real situations or predicting the effects of management action). Simply put: functioning holistic models are not yet available.

[108] The most important result from developing these models, however, is the potential to view the system as a whole and the fisheries as a whole. As these models are developed it becomes obvious that species interactions, spatial patterns and technical interactions can have a devastating effect on the outcomes of traditional methods of fisheries management.

[109] In particular, it follows from the analyses above that the use of any of the common regulatory systems alone may not suffice to maintain viable fisheries in multi-species ecosystems. In order to facilitate sustainable use of the resources, it is highly likely that a combination of most, if not all, systems is needed, including formal fleet reduction mechanisms.

[110] Complex models are needed in order to evaluate the effects of complex regulatory measures. These models need extensive data, which in many cases is not available, such as data on consumption or migration rates. The lack of data is not an indication that the models are too complex, but rather that the effect of the management measures cannot be predicted. If management is to be in accordance with the precautionary approach and data are lacking, there is a need to implement control measures that will work in spite of the added uncertainty. Interestingly, the temptation by management not to take such conservative action often goes contrary to economically rational utilization, which would advocate (very) low fishing mortality.

[111] In cases where data are available, the models can be used to evaluate the effects of control measures. In such cases it may be possible to reduce the size of a closed area or to demonstrate that a relaxation of the effort control will lead to greater catches without increasing the probability of overfishing. Such conclusions are rather unlikely, except in rare circumstances where fishing is at the bottom of the food chain.

[112] The models can also be used to evaluate the need for extensive data. Thus, the increased prediction accuracy obtained through more surveys or increased tagging can only be evaluated using corresponding models. The use of the models is therefore not only to advise management on control measures but also to advise on the data needed in order to be able to predict the effects of the measures.

[113] The basic tenets of single-species fish population dynamics probably need to be re-worded somewhat in the light of developments worldwide. In particular, rather than fishing at any (or the maximum) level that appears to be sustainable, it appears that an appropriate theme is to:

> Harvest marine resources using the minimum fleet size possible at that minimum level of fishing mortality that does not demonstrably lead to a serious long-term loss of catch.

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