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**Bio-economic Fishery Models and a Theoretical
Outline of Portfolio Theory**

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Abstract

A portfolio modelling approach holds the potential to satisfy the new tenets of fisheries management both in Europe and in the U.S. (if not globally); ecosystem based fisheries management (EBFM) and a Precautionary Approach. However, for any novel modelling methods to be applied, a background of fisheries models and current conceptual issues must be addressed. Without them, the model has no basis. This paper thus reviews single species modelling methods, which have become heavily criticized in the last three to four decades when determining the right level of harvesting activity within a fishery. Despite this, they are still commonly used by fisheries managers. As a result, the paper also focuses on alternative approaches, and treats of why single species models have not yet been fully replaced by these more highly developed and complex models. This then has inferences for how new models are to be used; as alternatives to existent methods, or as complements? A portfolio approach, geared as it is towards the management of risk, is argued to have a complementary role to play. The theoretical framework of portfolio theory is then reviewed and the various risk diversification intuitions of the model are discussed. Finally, in light of the different issues raised in this paper, the reasoning behind utilizing a portfolio approach to fisheries management is laid out.

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1. Single Species Bio-economic Models

The Gordon Schaefer model

One of the earliest bioeconomic models adopted in fisheries management was the Gordon-Schaefer model. The model arose out of the Verhulst (1838) equation in which it is assumed that the population growth of a marine species is limited by the availability of resources. Growth in Verhulst's logistic model is expressed by:

$$G(S) = rS \left(1 - \frac{S}{k}\right) \quad (1)$$

Growth is depicted in terms of biomass per unit of time when S is the population size of the fish stock (biomass), r is the growth rate of the stock under zero limitation of resources (or the intrinsic growth rate) and k is the carrying capacity representing the maximum population that can be expected with limited resources (maximum equilibrium biomass the environment can hold). Under natural equilibrium conditions (without fishing) surplus growth, or changes in biomass weight, equals zero ($G(S) = 0$ since $S = k$). This holds because the natural equilibrium carrying capacity of the ecosystem will be remained at, unless some exogenous force interferes and pushes the total biomass away from its average.

Assuming that no such interference occurs, equilibrium population size will, on average, remain more or less the same, meaning zero growth. The intuition behind the parabolic growth function is that at relatively low stock levels there will be less competition for food and living space such that individuals mature and reproduce at a faster rate. The extent of these advantageous conditions will diminish as population size increases such that the level of growth in the population will approach zero. The level of biomass at which growth is zero is known as the natural equilibrium size. The bell shaped relationship between stock size and stock growth rate is demonstrated graphically in figure 1 in the appendix.

The Verhulst equation is transformed into a catch-effort model by introducing the catch rate or harvest, as did Schaefer (1954). With this inclusion, the impact of fishing on the equilibrium level can be quantified, or in other words, with the addition of a new predator into the ecosystem (man) a new equilibrium is created. This is done by assuming firstly that fishing effort is a constant proportion of the stock and secondly

that harvest is always equal to the stock's surplus growth (Hannesson, 1993). Given this, the catch per unit of effort is proportional to and has a linear relationship with the population size:

$$H = Y = EqS \quad (2)$$

where Y is the yield, or catch/harvest (H) of fish, E is fishing effort and q is what is known as the catchability coefficient. Intuitively, because growth was otherwise zero, and some external disturbance was all that could divert it from that value, the scale of catchment (which we can consider to be that external disturbance) will equal the growth level of the stock and thus $Y=G(S)$. In other words, harvest will be equal to the new natural growth rate because the stock would begin to return to the natural equilibrium size if otherwise undisturbed. This gives,

$$EqS = rS \left(1 - \frac{S}{k}\right) \quad (3)$$

which means that at the new equilibrium level growth again becomes,

$$\frac{dS}{dt} = G(S) - Y = 0 \quad (4)$$

This simply represents the net growth in the stock per unit of time, say one year. Man's fishing effort constitutes a reduction in the carrying capacity of the ecosystem and therefore again, when at the natural equilibrium size, stock biomass does not deviate from this average. Theoretically, if fishing stopped, it would return towards the natural equilibrium size at the relevant growth rate, but assuming fishing effort and thus catch remains constant, that growth rate will be zero. The new equilibrium biomass, now a function of effort, is then written as

$$S(E) = k \left(1 - \frac{q}{r} E\right) \quad (5)$$

Inserting this into the harvest equation yields

$$H(E) = qkE \left(1 - \frac{q}{r}E\right) \quad (6)$$

This relationship is shown graphically in figure 2 in the appendix. The harvest, H^* , and stock size S^* , are now determined by the level of effort. Economic information is not represented by the model yet, but one can envisage that if marginal costs equal marginal revenue at S^* , then that is the level of exploitation that will take place in an open access fishery. In the long run, harvests will be below what they could be because growth at H^* is far lower than growth at the highest point on the bell curve. This suggests that initial moves towards higher effort will increase catches in the short run (by reducing stock to S^*), but at some pivotal point (over longer time horizons) will end up reducing them.

Equation (6) can be used to find the critical point of biomass and level of effort that will maximize this sustainable yield, whereby catch is maximized without entering the sphere of unsustainable exploitation. Solving the above equation by maximizing the values of S and E we get $S=k/2$ and $E=r/2q$. These relationships can be plotted to show the yield-effort curve that the Schaefer framework presents (See figure 3 in the appendix). The maximum sustainable yield (MSY)¹ has been reached where $E=r/2q$. Beyond this point, increases in effort only act to reduce the yield until such a point as yield is zero, r/q .

Gordon (1953, 1954) used Schaefer's biological model to develop an economic model. The mechanism which allows the Gordon model to establish this is the assumption that net revenues, π , derived from fishing are a function of total sustainable revenues (TSR) and total costs (TC):

$$\pi = TSR - TC \quad (7)$$

or, alternatively,

¹ MSY is the greatest long term average rate of exploitation of a fishery that can be sustained without reducing the ability of the fish stock to reproduce and maintain current stock biomass.

$$\pi = pY - cE \quad (8)$$

where p is the (constant) price of the species and c is the (constant) costs per unit of effort. No distinction is made between fixed, variable and opportunity (of labour and capital) costs. Substituting (8) into the harvest or yield equation (2) gives

$$\pi = (pqS - c)f \quad (9)$$

The economic equilibrium (of an open access fishery), much like the biological equilibrium, occurs when TSR is equal to TC, i.e. when $\pi = 0$. At this point, no new vessels will enter the fishery and none will exit. Because man's determined level of exploitation becomes constant at this economic equilibrium, the biological equilibrium will be established by it. This is so because in the Schaefer model a constant level of human exploitation means that the average population biomass does not deviate away from the new biological equilibrium which human involvement in the ecosystem has created. This 'simultaneous equilibrium' posited by the Gordon-Schaefer model is thus known as the bioeconomic equilibrium (BE). Stock biomass at bioeconomic equilibrium S_{BE} can thus be inferred by solving equation (9) for S :

$$S_{BE} = \frac{c}{qp} \quad (10)$$

Because effort will be reduced/ceased when $TC \geq TSR$, the model predicts that S will never equal zero and will always be positive (there will be no extinction). However, because open access, free market type conditions will promote the entry of new participants into the fishery until $\pi = 0$, the model predicts overexploitation, that is, it predicts that the actual yield of the fishery will be well below MSY (in the long run) and that effort will be much higher than is needed to achieve MSY (the TC curve will intersect the TSR curve at higher effort levels than those required to operate at MSY). Like the sustainable yield curve the TSR curve will be a function of effort but will represent financial productivity. Thus TSR can be calculated by multiplying the yield-effort equation $EqS = rS \left(1 - \frac{S}{K}\right)$ by the unit price:

$$TSR = prS\left(1 - \frac{S}{k}\right) \quad (11)$$

TC is calculated by making cost a function of the catch per unit of effort equation (2) and (3) where recall that $Y = EqS = rS\left(1 - \frac{S}{k}\right)$. Solving for effort E and multiplying out by cost gives the long term function of TC :

$$TC = \frac{cr\left(1 - \frac{S}{k}\right)}{q} \quad (12)$$

With all these relationships now defined, the long-run sustainable biomass and production functions of the fishery can be built in the Gordon-Schaefer model by specifying the corresponding levels of fishing effort at Maximum Economic Yield (MEY)², MSY and BE .

The above is a useful model for highlighting the key traits of a single species bioeconomic model. One important point to make clear before continuing however is that while the Gordon Schaefer model is ideal for this purpose (and is still one of the most popular models in use for fisheries management) it is not the full story. There are many other varieties of single species models that exist. More advanced single species models, in a bid to include more dynamic and realistic growth and mortality patterns, become more complex. It is outside the scope of this paper to review these differences (see Hilborn and Walters, 1992; Quinn and Deriso, 1999; Haddon, 2001), but the crucial point is that despite adaption's of mathematical expressions and functional forms to depict the growth and mortality rates of marine species more accurately, these two crucial variables are considered in isolation under a single species modelling framework. In an actual ecosystem, growth and mortality are determined by diverse ecosystem factors which are omitted from consideration when using single species modelling approaches alone.

² MEY occurs at a point to the left of MSY . Recall that MSY is the uppermost point on the parabolic growth curve. Costs increase with effort, and thus the cost curve will have a positive slope; it therefore cannot be tangential to the growth function curve at its highest point. In terms of economic efficiency it is desirable, and otherwise would be the case, that $MEY=MSY$.

Shortcomings of the Single Species Approach

Single species models attribute the equilibrium biomass of a species and changes in it to:

1. Recruitment, the biomass weight of fish entering the catchable population during the period
2. Individual growth, the biomass weight of the growth of individual fish within the population during the period
3. Natural mortality, the biomass weight of fish lost from the population due to natural death and predation during the period

(Anderson, 1977). Marine ecosystems consist of complex food chains with unfathomable degrees of species inter-relatedness; species ranging from tiny planktonic organisms that comprise the base of the marine food web (i.e., phytoplankton and zooplankton) right up to the largest mammals, sharks and predator fish species. Salinity, oceanic temperatures and prevailing currents, numbers and feeding habits of other species of fish, the amount of radiated solar energy, the rate of photosynthesis and the rate at which mineral elements are replaced are some of the vitally important environmental parameters that go into determining the natural equilibrium size of a species' biomass and the rate of growth in approaching it (Anderson, 1977).

These factors have consequences for the predictive power and accuracy of single species models. For example, the assumption of constant mortality in many single species modelling approaches 'places the annual variance in predation mortality into other sources of variability within the assessment (e.g. measurement error when turned to fishery independent data)' (Hollowed, et al., 2000). To highlight this point, suppose that data about the primary predator of a fisher's target species exists, such as its population size and the percentage of its diet made up of the fisher's target species.

Under a single species framework, the ability of this information to play a hand in more accurately predicting variation in the equilibrium size of the target species will be wasted, and the predictive power of variation in the predator species will simply become ‘measurement error’.

2. Alternatives to the Single Species Approach

Criticisms of single species fishery models and the concept of MSY as a fishery management tool are not new things in the literature, nor is trying to develop superior alternatives. Larkin (1977) wrote the now famous epitaph, ‘Farewell to M.S.Y’, specifying its period of use as the 1930s to the 1970s. In it, he contended that ‘we urgently need the same kind of morality, but we also need much more sophistication’. It is interesting to note that even in far more recent years the two major concepts that have come to prominence in the fisheries literature arise out of the same desires for sophistication and morality. The first is a call for further management sophistication through an ecosystem-based approach to fisheries management (EBFM) and the second, in the face of failures to achieve that sophistication hinges on morality, and a Precautionary Approach (there is a discussion of these two concepts in the policy and literature review chapter).

To overcome the shortcomings of single species models and achieve further ‘sophistication’, multispecies approaches try to model the relationships which the target species has with other species in the ecosystem. Today, data on predator or prey species is routinely used to model fish stock dynamics of given fisheries. Furthermore, marine ecologists have developed structural ecosystem models such as Ecopath which is then combined with Ecoism (a user friendly interface for fishery managers) to determine optimal total allowable catch (TAC)³ across species (Sanchirico, et al., 2006). However as Sanchirico et al. (2006) point out, even though advances in food web models for marine systems make structural modelling a more realistic option for achieving EBFM, they are costly to develop, data intensive, and subject to high levels of uncertainty with respect to species interactions, effects of fishing and environmental factors.

³ TAC is the fraction of MSY which each fishing license is permitted to harvest

There is still a lot to be learned about marine ecosystems, and the data intensive nature of structural models combined with the sensitivity of their results to small changes in the biological parameters are a cause for concern, especially when we consider the level of difficulty in obtaining sound marine ecosystem data to begin with. The logical deduction then, is that despite longstanding criticisms of single species models, a viable alternative has not yet been fully developed to take their place. The consequence is a trend among fisheries managers and scientists to incorporate numerous types of models into management strategies, be they single-species, multiple, or otherwise. Thus one should not view single species modelling as an outdated or redundant method and multi-species or structural modelling as a superior replacement, rather, the key issue to grasp is that the modelling of marine ecosystems is a tricky business and the goal of developing new models is to complement that which already exists. To highlight this point, the author refers to the minutes of an FAO focus group for the bioeconomic modelling of demersal fisheries off the Gulf of Thailand:

“Models should be seen as simplifications of reality. Adding complexity may, as is well known from multiple regression analysis, lead to a better data fit but may also decrease a model’s capability for making predictions. Therefore, it is often advisable to use as simple a model as possible to capture the essence of the challenges posed. There are several angles to this: Firstly, one should not generally expect that the construction of a very detailed model aimed at addressing all issues related to bio-economic (including ecological, economical and social) aspects of the fisheries of the Gulf of Thailand would be feasible or desirable. Even if such a model could be constructed, there would be no certainty that its predictions would be reasonable. Therefore, the direction taken by this workshop has been to utilize several models, which show some overlap in the predictions they make, but which are based on independent approaches for obtaining their results. If such different models come up with similar results, there is greater confidence that the results are robust. If not, the properties of the models can be investigated in search of explanations for the differences”.

Gaps in the science of marine biological modelling which determine the management decisions of a fishery cannot be expected to go away soon. This would explain the

logic of advocates of the Precautionary Approach who simply assert that precautionary provisions are needed as a safeguard against ill informed decision making. Essentially, scientific understanding of marine resources may come later, while policy decisions relating to marine resources have to be made in the present, i.e. under uncertainty. Those involved in fisheries research and development of new fisheries models are charged then with two tasks: firstly, to complement existing models with alternative ecosystem and multi-species based approaches to fisheries management and secondly, to assist in the incorporation of risk and uncertainty into fisheries management decision making frameworks. Adapting portfolio theory for these purposes has already been proposed in M.Phil term paper one. In the next section, a background of portfolio theory is provided and the theoretical framework is described in detail and discussed.

3. Mean Variance Portfolio Theory

One way in which asset managers or insurance companies attempt to ‘hedge’ themselves from potential financial losses is through the construction of portfolios of assets. The emergence of portfolio theory (Markowitz, 1952) from the field of financial economics gave asset managers and insurance companies a more formally developed theoretical framework through which optimal investment portfolios could be constructed by maximizing returns with respect to risk. In outlining portfolio theory I have relied heavily on the Elton, et al. (2003) text, *Modern Portfolio Theory and Investment Analysis*. From that text, the expected value of an asset with an uncertain future value is arrived at by summing each possible value (outcome) by the probability of its occurrence:

$$\bar{R}_i = \sum_{j=1}^M P_{ij} R_{ij} \quad (13)$$

where \bar{R}_i is the expected return of i th asset, R_{ij} is the j th return on the i th asset and P_{ij} is the probability of the j th return on the i th asset. Of course the predicted return, or expected value, will not always be equal to the observed return. This measurement error (variance) is given by,

$$\sigma_i^2 = \sum_{j=1}^M [P_{ij}(R_{ij} - \bar{R}_i)^2] \quad (14)$$

The return on a portfolio of assets is simply the weighted average of the return on the individual assets. The weight applied to each return is the fraction of the portfolio invested in that asset; call it X_i for the i th asset. The expected value of the sum of various returns for a portfolio of N assets is,

$$\bar{R}_p = \sum_i^N (X_i \bar{R}_i) \quad (15)$$

While portfolio return is just the weighted average of individual asset returns, portfolio variance is calculated a little differently. This subtle difference is the basis for portfolio theory's use as a risk management tool. Imagine a portfolio P , made up of two assets. Similarly to the calculation of portfolio return, the calculation of portfolio variance includes the weighted average of each asset's variance;

$$X_1^2 \sigma_1^2 + X_2^2 \sigma_2^2 \quad (16)$$

However the degree of covariance between assets 1 and 2 has the potential to reduce the overall variance of the portfolio, that is, each asset's price volatility has the potential to counteract the others (so long as they do not move in exactly the same way i.e. have perfectly positive correlation). This relationship has to be represented to accurately depict portfolio variance. The covariance between the two assets is given by,

$$\sigma_{12} = E \left[(R_1 - \bar{R}_1)(R_2 - \bar{R}_2) \right] \quad (17)$$

and because the magnitude of this covariance within the overall portfolio variance will be determined by each asset's weighting within the portfolio, it is written as,

$$2X_1 X_2 \sigma_{12} \quad (18)$$

Thus portfolio variance will be given by (17) and (18);

$$\sigma_p^2 = X_1^2 \sigma_1^2 + X_2^2 \sigma_2^2 + 2X_1 X_2 \sigma_{12} \quad (19)$$

The portfolio variance is therefore determined by multiplying the variance of each asset by its weighting in the portfolio, plus the covariance term. Assuming assets price fluctuations are not perfectly positively correlated, a lack of symmetry in price fluctuations should reduce portfolio variance. Note that because $2X_{\{1\}}X_{\{2\}}\sigma_{\{12\}}$ is the expected value of the product of two different deviations on assets one and two, as in equation (18), it can be positive or negative. If outcomes (good or bad, positive or negative) occur together, i.e. asset values move in the same direction, then the covariance term (and correspondingly portfolio variance) will be large also. However, if good outcomes for asset one are linked with bad outcomes for asset two, then the counteractive affect will result in a lower covariance and lower overall portfolio variance. For a portfolio of N assets, portfolio variance is written as,

$$\sum_{i=1}^N (X_i^2 \sigma_i^2) + \sum_{j=1}^N \sum_{k=1, k \neq j}^N X_j X_k \sigma_{jk} \quad (20)$$

which is the sum of all variances of individual assets in the portfolio plus the sum of all the covariance terms of assets in the portfolio with each other. The end result for a portfolio of risky assets is the cancelling out of idiosyncratic risk⁴ in individual assets which approaches zero as N becomes larger. Then only systematic risks⁵ remain. For the portfolio/asset manager this constitutes a useful means of controlling risk so that effort, attention and predictions about risks can focus on the systematic kind and avoid wasteful considerations of all the small individual risks that exist.

To delve deeper into the portfolio theory framework and relate its useful applications to fisheries management issues, it is necessary to focus on the geometric interpretation of asset combinations. The theory goes that it is possible to plot all conceivable risky assets (and combinations of them) in terms of their risk and return tradeoffs. Since investors are assumed to be risk averse in the portfolio theory framework and since

⁴ In finance, idiosyncratic risks are micro level, firm specific risks which other firms/assets are not subject to.

⁵ In finance, systematic risk is any macro level risk factor to which all firms/assets share exposure. Interest rates, exchange rates, and stock market indexes are all examples of systematic risks which affect the value of financial assets. In a fisheries adapted portfolio model, one can envisage such macro level risks being interpreted as large scale environmental or oceanographic factors to which all marine organisms share sensitivity.

they gain utility from return, combinations of assets that do not maximize return for a given level of risk (or minimize risk for a given level of return) are not optimal and therefore can be 'dropped' from consideration when allocating portfolios efficiently. Plotting the remaining combinations of assets that satisfy these criteria will lead to the creation of what is known as the efficient frontier. The efficient frontier is the set of portfolios that are available to the investor that yield different levels of return and for which no more risk than necessary need be taken on.

Which portfolio the investor chooses will relate to their risk preference. For example a highly risk averse investor would prefer low returns with low volatility whereas a less risk averse investor may be willing to take on more portfolio volatility for the chance of a higher return. Figure 4 in the appendix shows the risk-return efficient frontier that resulted from twenty optimal combinations of three assets. Time series returns for the three assets were generated randomly using the software programme Matlab and the optimal portfolios that make up the efficient frontier were delineated using this software also. Below the efficient frontier there are many combinations of assets that a portfolio manager could create, but according to the framework, any of these combinations would be sub-optimal because a portfolio yielding the same return which lay on the efficient frontier could be constructed with a lower expected variance. In this graphical example, the frontier consists of only twenty possible portfolio combinations of the three assets, but theoretically the efficient frontier can be made up of infinite optimal combinations of the universe of assets⁶.

A Portfolio Approach to Fisheries Management: Why?

From the previous treatment of single species models, their short comings and existent alternatives, several points emerged:

1. Criticisms of single species models are well founded, but sufficiently superior models that can completely replace them have not yet been developed.

⁶ 'Universe of assets' is an abstract, largely academic term used to describe an infinite number of assets that may exist. It is needed to mathematically satisfy the efficiency assumption which portfolio theory makes about of the efficient frontier.

2. Highly sophisticated models of marine multi-species relationships and ecosystem structural models have been developed, and while they cannot replace the single species approach, act as useful tools to assess/manage fisheries and marine ecosystems
3. This previous fact has led to more sophisticated multi-species/structural models being used as “complements” to existent fishery management approaches and single species modelling methods. Even with the highly complex structural models that have been developed, it is not necessarily desirable to completely “do away” with single species approaches in favour of highly complex alternatives. Policy considerations are best served by using various modelling techniques ‘to capture the essence of the challenges posed’ (Hin, 2000). Thus a set rule ideology relying on ‘the best’ model can be viewed as inferior to an adaptive, multi-model approach to managing a fishery and determining its MSY.
4. Marine ecosystems are highly complex and difficult to observe and therefore often defy scientific efforts to understand them. Any potentially negative impacts resulting from said modes of exploitation can therefore not be known with certainty. This unavoidable circumstance dictates that while resource exploitation may continue, fisheries managers must/should also ensure that risk management measures are taken to protect resources from overly negative outcomes such as stock collapse or habitat destruction. They therefore require models which focus on risk management and uncertainty to aid this decision making process. Additionally, fishers themselves face risks, accruing to prices, costs, stock biomass fluctuations and legislation change. It is desirable that fisheries managers utilize models which can inform them about such considerations.
5. Finally, as was discussed in the Literature Review, there is a demand for models that move towards formalizing EBFM and a Precautionary Approach.

4. Conclusions

The first three points above would suggest that there is no shortage of demand for new and complementary models for fisheries management. A portfolio modelling approach would constitute another vantage point through which to investigate potential fisheries management decisions. The usefulness of this vantage point (given inescapable uncertainty when modelling ecosystems) would be the portfolio approaches explicit treatment of risk. Finally, in terms of achieving EBFM, portfolio theory is concerned with optimal portfolio allocation given the interrelatedness of multiple assets; from a fisheries perspective the logic can be adapted to account for species' interrelatedness and shared sensitivity to fishing effort within a fishery. A Precautionary Approach can be built into a portfolio approach, by constraining fishing effort (reducing MSY) from a portfolio perspective, as opposed to at an individual species level as is currently the case.

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