A contribution to the economics of multispecies harvesting with special attention to the Barents Sea fisheries

by

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June 1990

CONTENTS

SUMMARY

1. Introduction

This is a thesis on the utilization of renewable resources with species interactions, within the field of natural resource economics. It comprises theoretical analysis as well as empirical application of the theory to the fisheries of the Barents Sea and adjacent areas, and consists of the following monograph and two papers:

1. The Economics of Multispecies Harvesting – Theory and Application to the Barents Sea Fisheries. Springer-Verlag. Berlin–Tokyo (1988).

2. The Economics of Predator–Prey Harvesting, in Rights Based Fishing (eds. P.A. Neher, R. Arnason and N. Mollett) 485–503, Kluwer Academic Publ. Dordrecht–London (1989).

3. Bioeconomics of Sustainable Harvest of Competing Species. *J. of Environm. Econ. and Managem.* Forthcoming.

In this text we shall refer to these as Papers 1, 2 and 3, respectively.

Within the field of fisheries economics especially two kinds of questions are raised. First, what does an open access harvesting regime imply for the levels of the resource stock, fishing effort and harvest rate? Second, what is the economic optimal resource stock, fishing effort and harvest rate, and furthermore, how can this economic solution be implemented by means of harvest fees, effort taxes or quantitative control of the fishing activities? To answer such questions it is common to assume that the Pareto-criterions are fulfilled for the rest of the economy. That is, the only externality to be considered is the one in the fishing industry, therefore the problem is of a "first-best" nature.

It is well-known from the theory of "second-best" that if one of the conditions for Pareto-optimum for one or another reason is not fulfilled, neither should the others be in general (Lipsey and Lancaster, 1956). As noted above it is quite common in the field of fisheries economics, as well as in natural resource economics in general, to assume that

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the problem considered is one of "first-best" nature. This, however, does not mean that the real economy is in such a state, but the assumption should rather be looked upon as a simplifying one to keep the analysis within a reasonable limit. When interpreting the results of the analysis, one obviously must take account of the limits the assumptions impose, in particular if the implications for management are going to be applied to the industry.

The assumption that the resource management problem is of "first-best" nature may be compared to that of the normative theory of taxation where the state of comparison very often is a "first-best" economy with lump sum transfers as the system of taxation. Nevertheless, every economist knows that such a system hardly exists in the real world. The advantage of this approach is, however, that problems of efficiency can be handled in a stringent way. The literature on economics of fisheries nearly always consider problems of "first-best" nature. This thesis follows that tradition. The next section classifies the literature on fisheries economics and places this thesis in the proper group. Each of the three parts of the thesis are summarized and discussed in the subsequent sections.

2. Classification of fisheries economics models and analysis

Fisheries economics models and analysis may be classified in several ways, for example in static and dynamic, or, theoretical and empirical, or, deterministic and stochastic models. Figure 1 illustrates a classification suitable for this particular thesis. The main distinction is between singlespecies and multispecies models. Singlespecies models are further divided into autonomous and non-autonomous models, where the former are characterized by their time invariant parameters. The multispecies models may have biological or harvest technological interactions. In the front of figure 1 the deterministic models are classified as dynamic or static depending on whether they discount future benefits and costs or not. Stochastic models explicitly take care of the uncertainty prevalent in most biological and economic systems.

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	Singlespecies		Multispecies	
	Autonomous	Non-autonomous	Biological interaction	Harvest interaction
Static	1	4	7	10
Dynamic	2	5	8	11
Stochastic	3	6	9	12

Figure 1. Classification of fisheries economic models and analyses.

Let us now go through the 12 groups of fisheries economics models and briefly discuss some of the main works in the field.

Models in the first group, static, autonomous singlespecies models, are the classics in fisheries economics theory. Gordon (1954) and Schaefer (1957) are the most famous ones. A Scandinavian thesis ought to mention the work of Warming (1911) as well, which includes the major elements of the theory of open access harvesting, later known under the heading "the tragedy of the commons".

Group 2, dynamic, autonomous singlespecies models, has its forerunner in non-technical analysis in Scott (1955) and Gordon (1956). Crutchfield and Zellner (1962) is the first attempt on mathematical formulation and solution of the dynamic harvesting problem by means of classical calculus of variation. This was a part of an empirical analysis of the Pacific-halibut fishery in the northeast Pacific. In the late 1960s and early 1970s optimal control theory became a standard tool in economics (Dorfman, 1969), especially in capital theory. Also in fisheries economics theory this tool was applied at an early stage (Plourde 1970, 1971; Quirk and Smith, 1970). Several papers applying control theory followed, with Clark and Munro (1975) and Clark (1976) among the most well-known. The former treats the resource stock as capital, and the interpretations of the solutions are similar to that of capital theory.

In the 1980s there has been an increasing interest in stochastic, autonomous single-species models of Group 3. Every fish resource shows smaller or greater variations in recruitment, growth and/or natural mortality. Also economic parameters such as market prices, ex-vessel prices, input prices etc. are important. Therefore, it is not a surprise that such variations more and more are explicitly included in fisheries economic models

and analysis (see e.g. Lewis, 1981; Andersen, 1982; Charles, 1983 a and b; Andersen and Sutinen, 1984; Clark, Munro and Charles, 1985; Spulber, 1985; and Hannesson, 1989).

Static, singlespecies models with non-autonomous parameters in Group 4 are, in a way, contradictory and have hardly any place in the literature. However, such models might be of pedagogical value to show how the optimal, or open access stock level, vary with the time variant parameters.

Dynamic, non-autonomous singlespecies models in Group 5, are of interest for the management of natural resources with intra- or inter-annual variations in biological or economic parameters. Papers on theoretical analyses of such phenomena includes Hannesson (1974) ch. 5.4; Clark and Munro (1975), Clark (1976) and Flaaten (1983). Henriksen (1986) is an application of this theory to the Barents Sea capelin fishery where non-autonomous biological as well as economic parameters are prevailing.

A model with stochastic recruitment and intra-annual, or seasonal, growth of a fish species would be an example of a singlespecies, stochastic, non-autonomous model in Group 6. Little has been published on this type of models yet, but elements in e.g. Flaaten (1983) and Hannesson (1989) may be integrated to form such models.

Group 7 comprises multispecies models with biological interaction between the species. Such interactions may be of predator–prey type, competitive or a combination of predator–prey and competition. Bioeconomic analysis of multispecies fisheries is fairly new, however, Larkin (1963) includes some economic elements. Maximizing combined yield of two species, having given constant weights to each of them, is equivalent to maximizing gross revenue from the combined fisheries. Hannesson (1974) ch. 3 and Anderson (1975) include fish prices as well as harvesting costs and maximizes the net economic yield from the combined harvest. Pikitch (1988) gives a thorough review of papers on fisheries with biological and technical interactions, mainly in the field of natural sciences.

Dynamic multispecies models with biological interactions, Group 8, explicitly take notice of the timelag between the investment/disinvestment in a natural resource and the altered harvest possibilities this gives. To make comparisons of revenues and costs

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at different points in time it is necessary to discount to the same point in time. Quirk and Smith (1970) is an early paper on this subject, but the somewhat complex model used does not make the interpretations of the results simple.

The two species model and the bioeconomic analysis in Clark (1976) ch. 9 is complex enough to include the biological interesting points, but still he manages to make the economic interpretations easy to compare with these of the singlespecies models. Other papers of interest in this group includes Silvert and Smith (1977), Hannesson (1983) and Conrad and Adu-Asamoah (1986). In the field of mathematical ecology there are several papers extending the analysis in the former. The latter includes, i.a. empirical analysis of the tuna fisheries in the eastern, tropical Atlantic, using a model of two competing species.

Group 9 comprises stochastic multispecis models with biological interactions. Mendelssohn (1980) and Yeung (1986) are examples of papers on this subject.

Static multispecies models with harvest interactions, Group 10, are valid for analysing fisheries where the gear simultaneously catches more than one species. Anderson (1975) is one of the very few bioeconomic papers in this group. European Communities (1987) gives a thorough review of fisheries where such externalities are prevalent.

The models of Group 11, dynamic multispecies models with harvest interactions, extend the analyses undertaken by Group 10 models by including the discounting of future revenues and costs. Clark (1976) ch. 9 includes dynamic analysis of technological interdependent fisheries.

Stochastic multispecies models with harvest technical interactions, Group 12, are nonexisting in the bioeconomic literature. Elements from the models in Group 9 may be useful in the analysis of Group 12 models.

All three parts of this thesis belong to Group 8, dynamic multispecies models with biological interactions. The subsequent sections of this summary are brief reviews of the three parts of the thesis with special emphasis on the question raised, the results found, the connections between the papers and how they are related to the literature in this field.

According to the introduction in Paper 1 the aim of that monograph is to give a

> ... methodological and quantitative analysis of multispecies fisheries, with
> an application to the Barents Sea fisheries.
>
> (Paper 1, p. 5.)

This is essentially the purpose of this thesis as well. To be more specific, the questions raised include: What are the open access equilibrium solutions for the fish stocks, fishing effort and harvest rates, and what are the corresponding optimal solutions? How are these solutions affected by changes in the economic parameters such as the ex-vessel prices of fish, harvesting costs and the discount rate? When are the implications for management of the two species models equivalent to that of singlespecies analysis? What is the adequate concept of multispecies models to be compared to the concept of maximum sustainable yield (MSY) known from the singlespecies models? What are the implications for management of different biological and economic objectives for the fisheries? Does a three species model add something to the analysis compared to that of a two species model?

In Paper 1 some of these questions are answered within a theoretical as well as an empirical context. The theory is applied to an investigation of the fisheries of the Barents Sea and adjacent areas. The three species Barents Sea model (the TSB-model) includes species at three different ecological levels: plankton preying fish, fish preying fish and fish preying sea mammals. At each ecological level two or more species are aggregated into one. In the following section is given a brief review of the 11 sections of Paper 1 and comparisons are made to the relevant literature on dynamic multispecies models with biological interactions. The subsequent two sections of this summary discuss Papers 2 and 3, respectively, which are purely theoretical, partly supporting the analysis of Paper 1 and partly extending the analysis of the latter by raising other related questions.

3. The economics of multispecies harvesting – theory and application to the Barents Sea fisheries

This monograph consists of 11 chapters and 12 appendices. The introduction gives a review of relevant biological and economic literature (published before 1986/87) and the purpose of the work is put forward. To understand the relative great emphasis put on the applied part of the work, including Flaaten (1984 a–c), it is of importance to stress the lack of an empirical based biological multispecies model for the Barents Sea when this work commenced. Biologists and other natural scientists are, however, currently working on such a model (see Tjelmeland and Bogstad, 1989).

Chapter 2 presents a fundamental predator–prey model from Leslie (1948) and May et al. (1979). In Ch. 3 the two species model is extended to include a top predator preying on the two other species, and whose carrying capacity depends on the total biomass of its preys. Selective harvest technology for each of the three species is introduced, and equilibrium stock levels are derived to be functions of biological and harvest technological parameters.

Hannesson (1983) is a theoretical analysis of a predator–prey system, and it is easy to show that the model he is using has the same isoclines as the model in ch. 2 of Paper 1. However, the dynamics of the two models are different. The questions raised in Paper 1 include the ones asked in Hannesson (1983), but the ways they are answered are different.

The three species model designed in ch. 3 is an extension of the three species models in May et al. (1979). This has been done to include the top predators of the Barents Sea, seals and whales, in the TSB-model. The sea mammals prey on the plankton feeders, capelin and herring, as well as on their main predators, cod, haddock and saithe. The three aggregated stocks are called sea mammals, capelin and cod. Another extension of the analysis compared to May et al. (1979) is the deduction of the equilibrium stocks as well as the conditions for equilibrium and stability, shown in appendices 1 and 8.

Based on Beddington and May (1980) it is shown in ch. 4 how to derive the limit to sustainable harvesting in a two species model. This limit proves to be a concave curve in

the yield plane of the two stocks, and it is named the maximum sustainable yield frontier (MSF). This compares to the production possibility frontier, known from the economic welfare theory, and is the two species model's correspondent to the MSY concept of singlespecies models. It is also shown in ch. 4 how to derive the MSF for the two stocks at the lowest ecological levels for a given stock level of the top predator. The alternative would be a possibility plane in the room of yields for the three species. The MSF curves, and the combination of stocks giving MSF, proves to be useful in the analysis of different economic and biological harvesting regimes in Paper 3.

Ch. 5 of Paper 1 gives a short review of the ecosystem of the Barents Sea, from phytoplankton and zooplankton to fish and sea mammals. In a global context this ecosystem is considered to be a simpel one, despite nearly 150 species of zooplankton and 115 species of fish. Of the approximately 25 species of sea mammals most of the whale species utilizes the Barents Sea, the coastal areas of Norway and the Norwegian Sea as feeding grounds in the summertime. Herring, capelin and cod make the larger part of the total biomass of fish, and these species have been the most valuable ones from a commercial point of view.

Ch. 6 explains the process of "guesstimating" the biological parameters of the TSB-model. The available set of data was too poor to use a standard estimation procedure to find the nine biological parameters. For some species reliable time series data were lacking, as well as precise estimates of the stock sizes. The main types of biological interactions among the stocks of the TSB-model have to some extent been known, in the meaning of which species eat which and how much, but not to such an extent that we could defend using traditional statistical methods. Instead we used what we called a "guesstimation" procedure:

> By "guesstimation" is meant, in this connection, that relevant biological liter-
> ature is studied and information essential to our problem is extracted. When
> two or more sources give somewhat different figures for the same variable,
> parameter etc., a choice is made as to which to rely on or the average of

them is used. All the steps and assumptions made are explained in detail so that the reader can critically appraise and modify them if that is felt to be desirable.

(Paper 1, pp. 35–36.)

To limit the attainable set of biological parameters of the TSB-model we demanded there should be some constraints on the yield and stock sizes of the model. The biological limits of the ecological system are the limits to sustainable economic development of the fisheries based on these resources. The set of biological parameters finally arrived at imply sustainable yields that do not contradict received biological knowledge for the species in the Barents Sea and adjacent areas.

Among the cited papers in Group 8 above, only Conrad and Adu-Asamoah (1986) include an empirical analysis of multispecies harvesting. It has been done partly by exogenous assigning of parameters and partly by using parameters estimated in single species contexts. Unless adjusted for, such use of parameters from single species models may cause distortions in the multispecies model. In Paper 1 the interactions between the three stocks have been taken notice of in the "guesstimation" procedure. Possible sustainable yield of one stock is therefore in tune with the possible sustainable yields of the other two stocks. Increasing the reliability of the biological part of the TSB-model, or other simple multispecies models, requires more methodological as well as empirical work. However, this research effort should rather be left to biologists, statisticians and other natural scientists. Nevertheless, recent literature in these fields seem to indicate that a partial approach to empirical multispecies modelling will still prevail for some time, see e.g. Magnusson and Pálsson (1989).

Ch. 7 is a theoretical bioeconomic analysis of multispecies harvesting. For a two species predator–prey model it is shown how the optimal equilibrium stocks are affected by changes in harvest prices, harvest costs and the social rate of discount. It is found that the optimal predator stock may increase by an increase in the discount rate. The effect on any of the stocks from an increased harvest price of the other species may be

positive or negative depending on the biological interactions and the net unit value of the harvest rates at the optimum. The effects on the optimal stock levels from changes in the economic parameters are analysed also in Hannesson (1983), but the model and the method used are different from what we have used in ch. 7. It is also shown in ch. 7 what to do when the optimal solution is not in the interior of the sustainable yield area.

The economic parameters of the TSB-model are calculated in ch. 8 by using data from i.a. the Norwegian accounting surveys for fishing vessels. These parameters are used in the bioeconomic analyses in the subsequent chapters of Paper 1.

The TSB-model's optimal equilibrium stock levels, harvest rates and economic rent are derived in ch. 9. Optimal harvest and effort taxes are also found. The basic case biological and economic parameters from the preceding chapters, the TSB-model implies a long run optimal equilibrium solution with the cod fishery as the dominant fishery. Capelin should not be harvested, but rather be left in the sea as feed for the cod. The sea mammals' consumption of cod and capelin is so significant that it pays to harvest them heavily. The optimal equilibrium stock level of the sea mammals is below the open access stock level, and therefore the harvest of these must be subsidized. Losses in this branch of the fishery is more than offset by he gains to be reaped in the cod fishery.

The conclusion that capelin should not be harvested at the optimum changes when, ceteris paribus, the price of capelin increases somewhat. *If* the total harvest could be sold for prices paid for roe-capelin and capelin for other consumption purposes, the optimal solution would be to keep the cod stock at a loss giving level and let the capelin fishery be the rent yielding one.

In scientific papers using control theory it is very often assumed that the optimum is an interior solution, i.e. that the parameter set is such that the optimum is not at the boundary of the attainable solutions. As shown in ch. 9, and noted above, the TSB-model implies an optimal solution at the boundary of the attainable set of solutions for the "basic case parameters". The test used to reveal such cases is described and explained, and the desired optimum is found.

The optimal equilibrium stock levels, harvest rates and the net present value of rent

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(NPV) from the combined fisheries are functions of biological and economic parameters. To investigate how sensitive these solutions are to changes in the parameters, we take the elasticities of these endogenous variables with respect to each of the parameters. We found that NPV is sensitive to changes in most of the biological and economic parameters related to the capelin and cod stocks, but rather insensitive to changes in the parameters related to the sea mammals. The optimal equilibrium stock of sea mammals increases with an increase in the social rate of discount.

As noted above boundary solutions are of interest in models such as the TSB-model. Other kinds of boundary, or corner solutions may arise in single species models, for example when there are several cohorts to be fished wholly or partly selectively, or when there are two or more types of vessels or gear fishing in a biomass model. The former type of corner solution arises in Hannesson (1978), while an example of the latter is found in Clark and Kirkwood (1979). The lack of examples in the fisheries economics literature on the kind of boundary solutions analysed in section 9 is probably because of the lack of applied multispecies models.

The optimal stock level for capelin derived in ch. 9 is, for the basic case parameters, greater than the pristine level. Such a result clearly is not possible to have in single species models. Henriksen (1984) found the optimal spawning biomass of capelin (*Mallotus villosus*) in the Barents Sea to be approximately 30% of the pristine stock level, using a 7% social rate of discount. Kristmannsson (1980) found the optimal spawning stock level of herring (*Clupea harrengus*) off Iceland to be 25–30% of the pristine level, using a 7% social rate of discount. Bjørndal (1987 and 1988) arrived at an optimal level of spawning biomass of North Sea herring equal to 40% of the pristine level in case of costless harvesting and 60% in case of stock dependent harvesting costs. In both cases the discount rate was 6%. All of these applied analyses of plankton preying fish stocks conclude with optimal relative equilibrium stock levels far below what we found for the stocks of the TSB-model. This should not come as a surprise knowing the important role of herring and capelin as transformers of plankton to fish in the north Atlantic.

In a bioeconomic analysis of cod (*Gadus morhua*) in the Barents Sea, Hannesson

(1978) does not explicitly state the optimal and the pristine stock levels, but implicitly they can be found. The former is somewhat larger than the MSY stock level, when using 10% social rate of discount. There are, to our knowledge, no published papers on bioeconomic singlespecies analysis to the Barents Sea area's stocks of seals and whales, but for other areas there are some. Clark (1985) pp. 25–27 analyses an aggregated stock of whales in the Antarctic and find the optimal equilibrium stock level to be approximately 35% of the pristine level, given a 5% social rate of discount. In a bioeconomic analysis of the harp seals (*Pagophilus groenlandicus*) in the northwest Atlantic Conrad and Bjørndal (1989) calculated the optimal stock level to 35% of the pristine level, given 6% discount rate and no stock dependent harvesting costs. Stock dependent harvesting costs would have increased the optimal stock level. In these two bioeconomic singlespecies analysis of sea mammals the optimal stock levels are significantly higher than found in the TSB-model, but still lower than the MSY stock level. The TSB-model includes the costs of predation which the sea mammals impose the capelin and cod fisheries, therefore, our results are reasonable compared to the results of the singlespecies analysis.

In ch. 10 of Paper 1 is shown the open access solution for the stock levels and harvest rates, provided that the Schaefer harvest function is valid in all three fisheries. Compared to the optimal solutions discussed in the preceding chapter there are especially two results which ought to be mentioned. First, the capelin stock is too heavily fished under an open access regime. Second, the sea mammals are harvested too lightly. Through history the relative rates of harvesting of the three ecological levels have changed dramatically, towards greater emphasis on the plankton preying species. This is probably a result of changes in relative prices and harvest costs of the three stocks.

Given the assumption of Schaefer harvest technologies in all three fisheries, none of the stocks of the TSB-model will be extinct under open access harvesting. This is in accordance with historical facts, with a couple of exceptions. However, with the current fish finding and gear technology, relying on historical facts and open access harvesting in the future may prove disastrous to many real fish stocks. An empirical analysis of the North Sea herring by Bjørndal and Conrad (1987) indicates that this stock probably

would have been extinct unless the fishery had been closed after the 1977-season. This despite their calculation of the long run open access equilibrium spawning stock level to approximately 10% of the pristine level. The reasons for this being partly the difference of the vessels adaptation in the short and in the long run, and the time delay between spawning and recruitment.

In the TSB-model each of the stocks is an aggregate of two or more real species close to each other in the ecological system. The question of extinction or not under open access harvesting should rather be answered for each of the real species since there are significant differences among some of them related to animal behaviour and gear technology. For example, the minke whale (*Balaenoptera acutorostrata*) is probably less vulnerable to extinction than the harp seals of the Barents Sea. The reason being that the former is distributed over a greater part of the sea, individuals are relatively small, and furthermore, they are difficult to spot when they come to the surface to breath for a very short time. The harp seals, however, congregate on the ice to give birth to pups and are easy to harvest during this period.

For a "high" price, or "low" harvesting cost of capelin it is shown in ch. 10 that open access harvesting will reduce this stock to such a low level that it can not sustain the cod stock at its open access level, implying that there will be no cod fishery in this case. Such cases were analysed theoretically in ch. 7. Obviously, it is not possible to have such results in deterministic singlespecies models, except for the trivial case when even the pristine stock level is below the minimum rent yielding level.

Ch. 11 summarizes Paper 1 and points out possible extensions of this work. Papers 2 and 3 extend the theoretical analysis of Paper 1. They will be briefly reviewed in the two following sections.

4. The economics of predator–prey harvesting

This paper, Paper 2, extends the predator–prey analysis of Paper 1 ch. 7, especially by investigating solutions at the boundary of the sustainable yield area. By using com-

parative statistics, the analysis, including the graphics and the calculus, could be kept very simple.

In section 3 is shown for which conditions the open access harvesting implies equilibria at the boundary of the sustainable yield area. Even if the pristine stock level is too low to economically sustain open access harvesting, this may change if the stock level of the predator is reduced by harvesting. Decreased stock level of the predator increases the stock size of the prey. On the other hand, profitable harvesting of the predator may become unprofitable if increased harvesting of the prey reduces this stock as well as that of the predator. Cases like this may occur because of exogenous changes in market prices and harvest costs.

In section 4 is shown that the optimal stock level of the prey can not be less than the open access level, whereas the optimal stock level of the predator may be below its own open access level. The latter case arises when the predator is a "trash" and the prey is an "inexpensive-to-catch valuable". It is also shown that increased discount rate implies increased optimal stock level of the predator when it is below its open access level. Increased discount rate always implies decreased optimal stock level of the prey. As noted above it is quite common in bioeconomic theory to assume that the optimal solution is an interior solution. In the case of predator–prey harvesting this would imply a solution within the sustainable yield area with positive harvest rates of both species. If the stock levels derived from the golden-rule equations do not satisfy these constraints, the optimal solution has to be found the way reviewed at the end of section 4.

Clark (1985) ch. 5.3 analyses predator–prey harvesting in general and shows that the optimal stock level of the predator may be below its open access level, whereas the prey species have to be above its open access level. As we have shown, the results may be different when solutions at the boundary of the sustainable yield area are allowed.

In Paper 1 ch. 7 we claimed to have found that the optimal stock level of the prey might increase with increased discount rate, whereas in Paper 2, section 4 it is found that the prey species always decrease with increased discount rate. The reason for these seemingly contradictory statements is that in the former case we did not distinguish

between interior and boundary solutions. When the optimal solution is at the boundary of the sustainable yield area with the predator as the only harvested species, increased discount rate implies decreased stock level of the predator and increased stock level of the prey. It is only in this case with no harvesting of the prey at the optimum that this species may increase with an increased discount rate. This also implies that even if a prey is left unexploited by man at a low rate of discount, it may be optimal to harvest this species at a higher rate of discount. The optimal solution in this case changes from a boundary solution to a solution in the interior of the sustainable yield area. Except for the cases of extinction of one species, boundary solutions have received little attention in the bioeconomic literature (see e.g. Hannesson (1983) and Clark (1985) ch. 5).

5. Bioeconomics of sustainable harvest of competing species

This paper, Paper 3, extends the two species analysis of Paper 1 ch. 7 to the case of two competing species. The main question asked is what are the implications for management of different biological and economic optimization criteria? The solutions found are compared both between them and with solutions from singlespecies analysis.

In section 3 is shown that the maximum sustainable yield frontier (MSF) is of the same importance in this Gause model of two competing species as the MSY is in singlespecies models. The combinations of stocks giving MSF form a hyperbola branch through the area of sustainable yields of the phase plane of the two species, whereas the MSY-stock level in singlespecies models is a single point at the biomass axis of the yield-biomass plane.

In section 4 is shown that economic rent may be earned for some combinations of stocks in the sustainable yield area. Given the Schaefer harvest functions the isoprofit lines prove to be ellipses. In case of costless harvesting it is shown that the graph through the points of maximum economic yield from the combined harvest of the two species is a part of a hyperbola branch lying outside the MSF hyperbola. In section 5 is shown that for various price ratios of the two species the graph through the points of maximum present value (MPV) of equilibrium rent is part of a hyperbola inside the MSF-hyperbola.

It is also shown that optimal harvesting may imply harvesting any of the two competing species at a loss at the equilibrium. The optimal equilibrium stock levels depend on the biological and economic parameters, and it is shown how the optimum is affected by changes in each of the economic parameters.

Compared to Paper 1, Paper 3 is different not only because of the analysis of two competing species instead of the predator–prey interactions analysed in the former. More important is the investigation of implications for management of various optimization criteria. Ecological conditions put restrictions on the sustainable economic development of the resource industries. In such a connection the ecological MSF criterion is merely a special case of the MPV criterion.

Paper 3 does not, like Paper 2, put emphasis on boundary solutions, except for the terminal points of the MSF, MEY and MPV graphs. The isoprofit ellipses and the hyperbolas of the MSF, MEY and MPV stocks have not been shown in the cited literature of Group 8. Neither has the result of the two hyperbolas making upper and lower bound of sustainable economic harvest of the two competing resources.

References

Andersen, P. (1982): Commercial fisheries under price uncertainly, J. of Environm. Econ. and Managm., 9, 11-28.

Andersen, P. and J.G. Sutinen (1984): Stochastic bioeconomics: a review of basic methods and results, Marine Resource Economics 1, 117-136.

Anderson, L.G. (1975): Analysis of open-access commercial exploitation and maximum economic yield in biologically and technologically interdependent fisheries. J. Fish. Res. Board Can. 32, 1825-1842.

Beddington and May (1980): Maximum sustainable yields in systems subject to harvesting at more than one throphic level. Math. Biosci. 51, 261-281.

Bjørndal, T. (1987): Production economics and optimal stock size in a north Atlantic fishery. Scandinavian J. of Economics 89 (2), 145-164.

Bjørndal, T. (1988): The optimal management of North sea herring. J. of Environm. Econ. and Managem. 15, 9-29.

Bjørndal, T. and J.M. Conrad (1987): The dynamics of an open access fishery. Canadian J. of Economics XX, 74-85.

Charles, A.T. (1983a): Optimal fisheries investment: Comparative dynamics for a deterministic seasonal fishery, Can. J. of Fish. and Aqua. Sci., 40, 2069-2079.

Charles, A.T. (1983b): Optimal fisheries investment under uncertainty, Can. J. of Fish. and Aqua. Sci., 40, 2080-2091.

Clark, C.W. (1976): Mathematical bioeconomics: the optimal management of renewable resources. New York. John Wiley & Sons.

Clark, C.W. (1985): Bioeconomic Modelling and Fisheries Management. John Wiley & Sons. New-York - Singapore.

Clark, C.W. and G.R. Munro (1975): The economic of fishing and modern capital theory. J. of Environm. Econ. and Managem. 2, 92-106.

Clark, C.W. and G.P. Kirkwood (1979): Bioeconomic model of the Gulf of the Carpentaria prawn fishery. J. of Fish. Res. Board of Canada 36, 1304-1312.

Clark, C.W., G.R. Munro and A.T. Charles (1985): Fisheries, dynamics and uncertainty, in "Progress in Natural Resource Economics" (A.D. Scott, ed.), Oxford University Press, Oxford, pp. 99-120.

Conrad, J.M. and R. Adu-Asamoah (1986): Single and multispecies systems: The case of tuna in the eastern tropical Atlantic. J. of Environm. Econ. and Managem. 13, 50-68.

Conrad, J. and T. Bjørndal (1989): A bioeconomic model of the Harp seal in the Northwest Atlantic. Working paper no. 41/1989, Centre for Applied Research, NHH, Bergen.

Crutchfield, J.A. and A. Zellner (1962): Economic aspects of the Pacific halibut fishery, Fishery Industrial Research Report 1, U.S. Dept. of the Interior, Washington D.C.

Dorfman, R. (1969): An economic interpretation of optimal control theory, American Economic Review 59, 817-831.

European Communities (1987): Assessment of technical interactions in mixed fisheries, Commission of European Communities, Brussels.

Flaaten, O. (1983): The optimal harvesting of a natural resource with seasonal growth, Can. J. of Econ., XVI, 447-462.

Flaaten, O. (1984a): Fiskebestandene i Barentshavet og tilgrensede områder. Del B: Bestandsberegninger 1950 - 1980 (Stock estimates of some fish species in the Barents Sea, 1950 - 1980. In Norwegian). Institute of Fisheries, Univ. of Tromsø (mimeo). Tromsø.

Flaaten, O. (1984b): Sel og hval i Barentshavet (Seals and whales in the Barents Sea. In Norwegian). Institute of Fisheries, Univ. of Tromsø (mimeo). Tromsø.

Flaaten, O. (1984c): Beregning av predasjonskoeffisientene i en tre-arts modell for Barentshavet (Estimates of the predation coefficients in the three-species Barents Sea model. In Norwegian). Inst. of Fisheries, Univ. of Tromsø (mimeo). Tromsø.

Gordon, H.S. (1954): Economic theory of a common-property resource: the fishery. J. of Political Economy, 62, 124-142.

Gordon, H.S. (1956): Obstacles to agreement on control in the fishing industry, in "The economics of fisheries", (R. Turvey and J. Wiseman, eds.) (FAO, UN, Rome) pp. 65-72.

Hannesson, R. (1974): Economics of Fisheries: Some Problems of Efficiency. Studentlitteratur. Lund.

Hannesson, R. (1978): Trålfiske eller skreifiske? Om optimal beskatning av den norsk-arktiske torsk. Økonomiske skrifter nr. 12. Institutt for økonomi, Universitetet i Bergen, Bergen.

Hannesson, R. (1983): Optimal harvesting of ecologically
    interdependent fish species. J. of Environm. Econ. and
    Managem. 10, 329-345.

Hannesson, R. (1989): Fixed or variable catch quotas? The
    importance of population dynamics and stock dependent cost,
    in "Rights Based Fishing" (P.A. Neher, R. Arnason and N.
    Mollett, eds.), Kluwer Academic Publ., Dordrecht - London,
    pp. 467-480.

Henriksen, E. (1984): Sommerloddefiske eller vinterloddefiske? En
    bioøkonomisk analyse av loddebestanden i Barentshavet.
    Hovedoppgave Institutt for Fiskerifag, Universitetet i
    Tromsø.

Kristmannsson, S. (1980): Sildefiske ved Island. En bioøkonomisk
    simuleringsmodell. Hovedoppgave. Institutt for Fiskerifag,
    Universitetet i Tromsø, Tromsø.

Larkin, P.A. (1963): Interspecific competition and exploitation.
    Journal of the Fisheries Research Board of Canada, Vol.20,
    pp. 647-678.

Leslie, P.H. (1948): Some further notes on the use of matrices in
    population dynamics. Biometrika, 35, 213-245.

Lewis, T. (1981): Exploitation of a renewable resource under
    uncertainty, Canadian J. of Economics, 14, 422-39.

Lipsey, R.L. and K. Lancaster (1956): The general theory of
    second-best, Rev. of Econ. Studies 24 (1), 11-32.

Magnússon, K.G. and O.K. Pálsson (1989): Predator-prey
    interactions of cod and capelin in Icelandic waters. Science
    Institute, University of Iceland, Reykjavik, RH-07-89.
    Mimeo.

May, R., J.R. Beddington, C.W. Clark, S.J. Holt and R.M. Laws,
    (1979):Management of multispecies fisheries. Science, Vol.
    205, pp. 267-277.

Mendelssohn, R. (1980): Managing stochastic multispecies models,
    Math. Biosci. 49, 249-261.

Pikitch, E.K. (1988): Objectives for biologically and technically
    interrelated fisheries, in "Fishery Science and Management -
    Objectives and Limitations". (W.S. Wooster, ed.). Springer-
    Verlag, Berlin - Tokyo.

Plourde, G.C. (1970): A simple model of replenishible resource
    exploitation, Am. Econ. Review 60, 518-522.

Plourde, G.C. (1971): Exploitation of common-property replenishible resources, Western Economic Journal 9, 256-266.

Quirk, J.P. and V.L. Smith (1970): Dynamic economic models of fishing, in "Economics of Fisheries Management: A Symposium" (A.D. Scott, ed.), University of British Columbia, Institute of Animal Resource Ecology, Vancouver, pp. 3-32.

Schaefer, M.B. (1954): Some aspects of the dynamics of population important to the management of some commercial marine fishes. Bull. Inter-Amer. Trop. Tuna Comn., Vol.1, 26-56.

Scaefer, M.B. (1957): Some considerations of population dynamics and economics in relation to the management of marien fishes. J. of the Fish. Res. Board of Canada, Vol.14, 669-681.

Scott, A.D. (1955): The fishery: The objectives of sole ownership. J. of Political Economy 63, 116-124.

Silvert, W. and W.R. Smith (1977): Optimal exploitation of a multispecies community, Mathematical Biosciences, 33, 121-134.

Spulber, D.F. (1985): Comment of "C.W. Clark et al.: Fisheries, dynamics and uncertainty", in "Progress in Natural Resource Economics" (A.D. Scott, ed.), Oxford University Press, Oxford, pp. 120-130.

Tjelmeland, S. and B. Bogstad (1989): Multspec: The Manual. Bergen. Institute of Marine Research (mimeo).

Warming, J. (1911): Om grundrente av fiskegrunde. Nationaløkonomisk Tidsskrift, 11, 499-505.

Yeung, D.W.K. (1986): Optimal management of replenishable resources in a predator-prey system with randomly fluctuaton population, Math. Biosci. 78, 91-105.