Strategic Dynamic Interaction: The Case of Barents Sea Fisheries

Ussif Rashid Sumaila

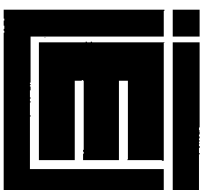# Strategic Dynamic Interaction: The Case of Barents Sea Fisheries

Ussif Rashid Sumaila

CHR. MICHELSEN INSTITUTE
Development Studies and Human Rights

Working Paper WP 1997: 1

Strategic Dynamic Interaction: The Case of Barents Sea Fisheries

Ussif Rashid Sumaila

Bergen, January 1997

Summary:

This paper develops a bioeconomic model for two Barents Sea fisheries that attempts to capture the predator-prey relationships betwen cod and capelin, the two main species in the habitat. The aim is to analyse joint (cooperative) versus separate (non-cooperative) management of this predator-prey system with a view to isolating the efficiency loss due to separate management. Using a game theoretic framework and a multicohort age structured biomodel, we compute joint and separate management equilibrium outcomes of the model, and investigate the effects of changes in economic parameters on the computed results. In this way, we explore the economic consequences of the predator-prey relationships between cod and capelin, and the externalities due to non-cooperation. Results of the study tend to suggest that (i) under current market conditions it is economically optimal to exploit both species (rather than just one of them) under joint management, (ii) in comparison with the separate management outcome, a severe reduction of the capelin fishery is called for under joint management, and (iii) the loss in discounted economic rent resulting from the externalities due to the natural interactions between the species is significant, reaching upto almost a quarter of what is achievable under separate management.

Indexing terms:
Game theory
Management
Fisheries
Cod; Capelin
Barents Sea

Contents

Introduction

The marine life in the Barents Sea supports two major fisheries, a fishery for cod and other demersal species, and a purse seine fishery for capelin. It is known that there is a predator-prey relationship between cod and capelin[1]. The purpose of this paper is to study the economic effects of this biological inter-relationship under different management arrangements. We develop a model that captures this relationship, thereafter we employ a numerical method to compute various equilibrium solutions of the model. First, Nash non-cooperative equilibrium solutions are determined when the two stocks are managed separately by their respective owners. Second, we identify joint management equilibrium solutions by assuming that exploitation and management of cod and capelin are carried out by a sole owner[2]. The latter solution is best in the sense that the sole owner is expected to internalise the externalities that are bound to originate from the natural interactions between the two species. Third, we allow the exploitation of only cod in order to investigate the economic merits of allowing cod to feed on capelin while only cod is harvested for human consumption. Note that cod is the more valuable of the two species.

Specifically, the main questions with which we are concerned in this paper include: (i) What is the maximum discounted economic rent that can be derived from the resource under joint and separate management? (ii) How significant is the difference between these two solutions? (iii) What is the effect of exploitation on the stock levels under these

---

[1] Eide and Flaaten (1992) gives a compact review of the ecosystem of the Barents sea fisheries.

[2] Contrast this with Flaaten and Armstrong (1991), where two variants of the cooperative (joint management) solution are discussed; one in which transfer payments are allowed and the other in which they are not. The sole ownership assumption here coincides with the "transfer payment" variant.

management regimes? (iv) Is it economically optimal to exploit both species at current market conditions? and (v) How are capelin harvest and predation traded-off against each other, given changes in prices, costs, and discount factors?

We begin by giving a short bibliographic note (section 2), then we set up a bioeconomic model for the cod-capelin fisheries of the Barents Sea in section 3. In section 4, we present data and the numerical results. The solution procedure for the model is relegated to an appendix. Finally, section 6 concludes.

Bibliographic note

Quirk and Smith (1970) and Anderson (1975) were among the first theoretical papers to appear in the fisheries economics literature that study the economics of ecologically interdependent fisheries. Both of these papers study and compare the free access equilibrium and the social optimum in such systems. They derive necessary conditions for optimum and interpret these in general terms. Hannesson (1983) extends the results of these two papers by finding answers to the following questions: (i) To what extend are the results of single-species theory valid also for multi-species theory? (ii) Is there a well-defined relative price of products obtained at different levels in the food chain at which harvesting should be switched from one species to the others? (iii) Will a stronger discounting of the future always imply a decreasing standing stock of biomass?

Three points should be noted about the above-mentioned works. First, none of the papers analyses strategic conflicts and interactions. Second, as in Silvert and Smith (1977) and May et al. (1979), these papers use slightly different versions of the Lotka-Volterra model

to characterise the multi-species systems they study. Hence, the implicit assumption in these papers is that the fish population is a homogeneous entity that can be adequately described by a single variable. Third, the papers are mainly theoretical, with very little or no empirical content, they are hence not applied to any specific fishery.

The fundamental game theoretic paper that analysed the problems associated with the joint management of fishery resources in detail is Munro (1979). The papers of direct bearing to this work are those of Fisher and Mirman (1992), and Flaaten and Armstrong (1991). These are theoretical analyses of interdependent renewable resources, which study game situations. In addition, these papers assume single cohort growth rules to derive general theoretical results. By contrast our paper, on one hand, is an empirical study of the Barents Sea fisheries, which explicitly recognises that fish grow with time and that the age groups of fish are important both biologically and economically; on the other hand, a central aspect of this paper is that it studies game situations and applies specific functions to analyse two specific fisheries. It is worth mentioning that these fisheries have previously been studied both biologically and economically for the purpose of finding the optimal rate of utilisation of the resources therein (Eide and Flaaten, 1992, Hamre and Tjelmeland, 1982). Nevertheless, this study should provide further insights into the problems involved. For instance, in contrast to this paper, Eide and Flaaten (1992) analyse only the sole ownership outcome.

The bioeconomic model

We model a multi-species system in which there are two biologically interdependent species. The interdependency derives from the fact that one of the species, that is, cod, predates the other, capelin. This biological interaction is captured here through the way we model the *weight of cod* and the *predation on capelin by cod*. The simple assumptions we make regarding these are (i) the weight of the predator (cod) is positively related to the density of capelin in the habitat, and (ii) the predation on capelin depends positively on the biomass of cod and the density of capelin in the habitat. It is also likely that the survival rate of cod will depend weakly on the abundance of good food, i.e., capelin. This effect is, however, considered negligible and thus ignored in this formulation. The formalisation of these assumptions are based on Moxnes (1992), which in turn is inspired by the MULTSIMP model developed by Tjelmeland (1990).

Capelin

The capelin fishery takes place in two seasons (the winter and summer fishing seasons) of approximately two months duration each. The winter capelin fishery exploits mature capelin on its way to the spawning grounds. The most important age group exploited by this fishery is 4, but some 3 and 5 year olds are caught as well. The summer capelin fishery exploits fish of 2 years and above. In this model, we concentrate the capelin fishery into the winter season only. The justification for this are threefold. First, the winter fishery is economically the more important of the two. Second, the winter fishery exploits mainly mature capelin, which are more valuable because they weigh more. Third, caught winter capelin is more likely to last longer than summer capelin since it normally has less organic

content in its diet. This is partly because capelin stops feeding before spawning, after which it dies. We assume all capelin mature at the age of 4 and confine the winter capelin fishery to age groups 3 and 4. Hence, there are four capelin age groups in our model. At the opening of a fishing season, a constant number of 1-year olds are recruited into the fishery. For a typical capelin cohort, a decrease in the stock comes from *natural* mortality, *fishing* mortality, and the *predatory* activities of cod on the cohort.

From now on we use the subscripts a ($a=1,..,A$) and t ($t=1,..,T$) to represent age groups of fish (both capelin and cod) and fishing periods, respectively; and the superscripts *co* and *ca* to refer to variables and parameters that relate to cod and capelin, respectively. Note that A and T denote the last age group and last fishing period, respectively.

Natural survival rate, s^{ca}, is assumed to be constant for all age groups. Fishing mortality is given by the harvest function,

(1) $$h_{a,t}^{ca} = q_a^{ca} e_t^{ca}$$

Where the parameter q_a^{ca} is the age-dependant catchability coefficient; and e_t^{ca} is the fishing effort exerted on capelin. We model the harvest function in this manner because capelin is a schooling species, hence, the assumption is that once capelin schools are located the fishing vessel is simply filled up in readiness for return to the port of call[3].

Following Moxnes (1992), we let the predation on age group a capelin in period t by cod, $p_{a,t}^{ca}$, be given by

(2) $$p_{a,t}^{ca} = \rho_t n_{a,t}^{ca}$$

---

[3] Clark and Kirkwood (1979) is one example where a similar formulation of the harvest function is applied.

where $n_{a,t}^{ca}$ is the number of age a capelin in period t; ρ_t, denoting relative predation, is

defined as the amount of capelin eaten by cod in period t divided by the total biomass of

capelin in that period. Hence, $p_{a,t}^{ca}$ is the number of age group a capelin eaten by cod in

period t.

The amount of capelin eaten is a function of both the biomass of the predator, B_{pred}, and the

density of the prey, $D_{prey} \geq 0$. Furthermore, when $D_{prey_t} = 1$, each cod is assumed to eat k_1

times its own weight. Thus, ρ_t can be expressed as

$$(3) \qquad \rho_t = \frac{k_1 D_{prey_t} B_{pred_t}}{B_{prey_t}}$$

Figure 1 below illustrates how relative predation varies with changes in the biomass ratio

(that is, biomass of predator divided by biomass of prey) at different prey densities. It is

seen from equation 3 and Figure 1 that an increase in the biomass ratio results in an

increase in relative predation, while an increase in prey density leads to an upward swing in

the relative predation curve.

Figure 1: Relative predation vs Biomass ratio at different levels of density of prey
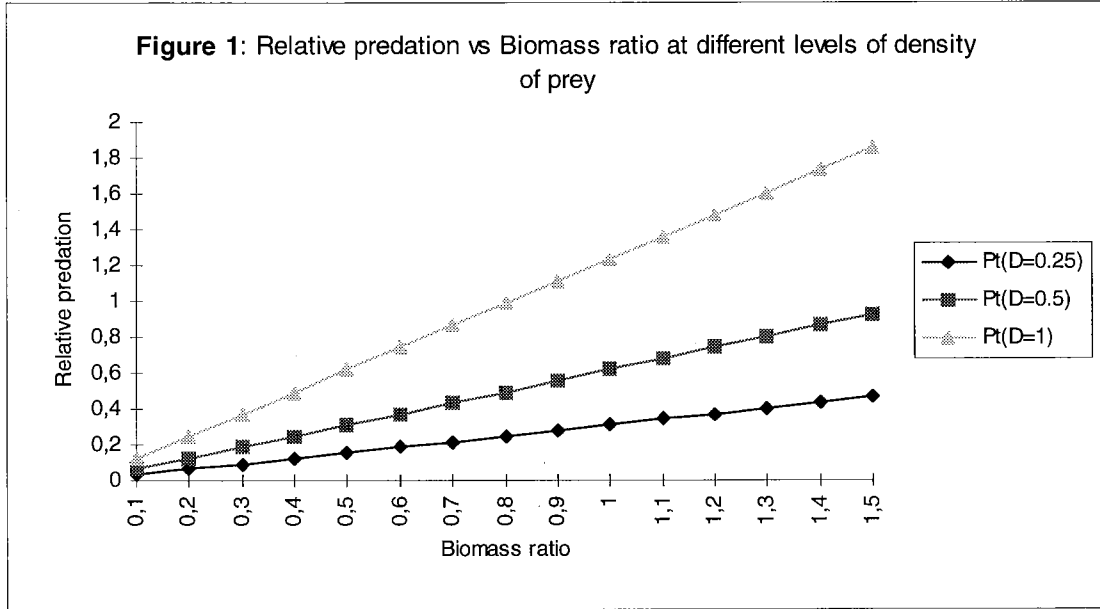
Note that when there is no capelin, $D_{prey_t} = 0$ and hence ρ_t is also zero. The density of

capelin in the habitat at time t, D_{prey_t}, is defined by the following equation (Moxnes, 1992)

$$(4) \qquad D_{prey_t} = \frac{D_{prey}^{max}}{1 + (D_{prey}^{max} - 1)(\dfrac{B_{prey_t}}{\tilde{B}_{prey}})^{-\beta}}$$

where $\tilde{B}_{prey}$ is a standard magnitude of capelin biomass at which $D_{prey} = 1$; D_{prey}^{max} is a

constant maximum factor by which cod will increase its normal intake of capelin (given by

k_1) at high densities of capelin; and $\beta > 0$ is a parameter. It is worth mentioning that the

above relationship corresponds to the type 2 functional response reported in Holling (1965).

We illustrate in Figure 2 the relationship between density of prey and prey biomass. As can

be seen the curve is concave.

Figure 2: Density vs Biomass of prey
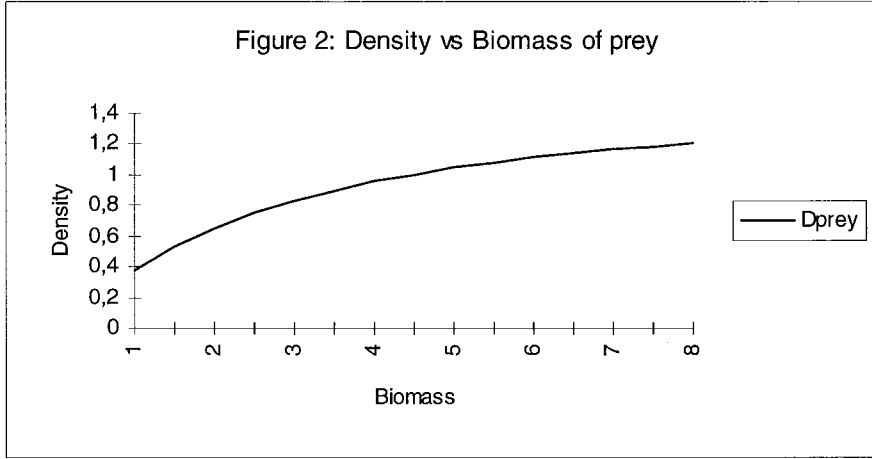
From the foregoing, the stock dynamics of the capelin stock can be represented by

$$n_{1,t}^{ca} = R^{ca}$$

$$n_{2,t}^{ca} \leq s^{ca} n_{1,t-1}^{ca} - p_{2,t}^{ca}$$

(5) $$n_{3,t}^{ca} + h_{3,t}^{ca} \leq s^{ca} n_{2,t-1}^{ca} - p_{3,t}^{ca}$$

$$n_{4,t}^{ca} + h_{4,t}^{ca} \leq s^{ca} n_{3,t-1}^{ca} - p_{4,t}^{ca}, \quad n_{4,t}^{ca} \geq E, \quad \forall t \geq 1; \quad n_{a,0}^{ca} \text{ given}.$$

In the above equation, $n_{a,0}^{ca}$ denotes the number of age a capelin at the start of the game; R^{ca}

is constant recruitment of capelin; and E represents the escapement required to maintain

recruitment of the stock. This escapement is set equal to half a million tonnes as

recommended by Hamre and Tjelmeland (1982). The stipulation of a minimum escapement

implies that recruitment of capelin can be regarded as independent of the stock level so long

as escapement does not occur below this threshold value.

Cod

In this case a typical cohort of cod decreases in number due to only *natural* and *fishing*

mortalities. But unlike in the case of capelin where weight of individuals in a given age

group is assumed to be constant, weight of cod is assumed to depend positively on the

density of capelin, D_{prey_t}. The dependence of the weight of age group a cod in period t on the density of capelin is captured mathematically by (see Moxnes, 1992):

(6) $$w_{a,t}^{co} = w_{a-1,t-1}^{co} + GW_{a0}(D_{prey_t}k_2 + (1-k_2)), \qquad w_{a,0}^{co} \ given$$

where $w_{a,0}^{co}$ is the weight of an individual in age group a cod (in kg) at the start of the game; GW_{a0} is normal growth rate of age group a cod; and k_2 denotes the relative importance of capelin as food for cod in relation to other sources of nutrition. Notice that when there is no capelin in the habitat, D_{prey_t} is equal to zero, and the growth of cod would then depend only on other sources of nutrition given by the expression $GW_{a0}(1-k_2)$. See Figure 3 for a plot of the equilibrium weights given by Equation (6) under separate and joint management[4].

For a given yearclass of cod the number of individuals decreases over time due to constant natural, and fishing mortalities, hence we have

(7)
$$n_{0,t}^{co} = f(B_{t-1}^{co}),$$
$$n_{a,t}^{co} + h_{a,t}^{co} \le s^{co}n_{a-1,t-1}^{co}, \qquad for \quad 0 < a < A,\ t > 0$$
$$n_{A,t}^{co} + h_{A,t}^{co} \le s^{co}(n_{A,t-1}^{co} + n_{A-1,t-1}^{co}), \quad n_{a,o}^{co} \ given.$$

where $f\left(B_{t-1}^{co}\right) = \dfrac{\chi B_{t-1}^{co}}{1 + \gamma B_{t-1}^{co}}$ is the Beverton-Holt recruitment function[5];

$B_{t-1}^{co} = \sum_a p_a w_{a,t-1}^{co} n_{a,t-1}$ represents spawning biomass in weight; p_a is the proportion of

---

[4] Note that equation (6) enters the profit function of the cod owner.

[5] Here, recruitment refers to the number of age zero fish that enter the habitat in each fishing period.

mature fish of age a; χ [6] and γ are constant biological parameters; s^{CO} is constant survival rate of cod, $n_{a,t}^{co}$ represents the post-catch number of age group a cod in fishing period t.

The harvest of age group a cod in fishing period t, is given by

$$(8) \qquad h_{a,t}^{co} = q_a^{co} n_{a,t}^{co} e_t^{co}$$

where e_t^{co} is the fishing effort exerted on cod; and q_a^{co} stands for the age dependent catchability coefficient of the cod harvesting vessels.

Notice that in contrast to Eide and Flaaten (1992), where constant recruitment is assumed for cod, we specify a recruitment function for cod and assume constant recruitment for capelin, mainly because capelin is a pelagic species, for which specifying a recruitment function is not an easy task[7].

Economics

Non-cooperative (separate) management

Suppose there are two agents (i.e., the owners), each of whom harvests only his own species. The fishery, hence, is organised under a cod and a capelin part, each managed by separate and distinct authorities. Organising the fishery in this way can be justified both because cod and capelin are exploited by different parties using completely different technologies (trawlers for cod and purse seiners for capelin), and the fact that the fishing grounds of the two species are partly different. By this supposition and the fact that it is

---

[6] χ = f´(0), is the number of recruits per unit weight of biomass "at zero" or the polutation level.

[7] Moxnes (1992), however, is a study where recruitment functions are specified for both cod and capelin.

hard to imagine any market interaction between cod and capelin, we isolate externalities that arise only from the natural interactions between the two species (see Fischer and Mirman, 1992).

The single period profit to the cod and capelin owners is derived from the sale of fish harvested. These are defined as

$$(9) \qquad \pi_t^{co} := v^{co} \sum_{a=4}^{A} w_{a,t}^{co} (D_{prey_t}) q_a^{co} n_{a,t}^{co} e_t^{co} - \frac{\psi^{co} e_t^{co^{1.01}}}{1.01}$$

for cod, and similarly

$$(10) \qquad \pi_t^{ca} := v^{ca} \sum_{a=3}^{4} w_{a,t}^{ca} q_a^{ca} e_t^{ca} - \frac{\psi^{ca} e_t^{ca^{1.01}}}{1.01}$$

for capelin. Here, the subscripts and superscripts are as defined earlier; v denotes price per kilogram of fish harvested; w represents weight; and ψ is the unit cost of hiring a given vessel type for one year. Notice that the single period profit to the cod owner depends on his own effort and the stock size of both species. The dependence on the capelin stock stems from the weight of cod as this depends partly on the density of capelin. On the other hand, the single period profit to the capelin owner depends only on his own effort, as weight of capelin is constant in this model.

Each owner is assumed to be interested in maximising the sum of his discounted profit. Thus the cod owner maximises

$$(11) \qquad \Pi^{co} := \sum_{t=1}^{T} \delta^{co^t} \pi_t^{co}$$

11

with respect to both own effort and own stock level, subject to the stock dynamics given by equation (7), and the obvious nonnegativity constraints. In equation (11), Π^{co} denotes the discounted sum of single period profits from cod; $\delta^{co} = \left(1 + r^{co}\right)^{-1}$ is the discount factor; $r^{co} > 0$ denotes the interest rate faced by the cod owner;

Similarly, the capelin owner maximises

$$(12) \qquad \Pi^{ca} := \sum_{t=1}^{T} \delta^{ca^{t}} \pi_t^{ca}$$

with respect to own effort level, subject to the stock dynamics given by equation (5), and the obvious nonnegativity constraints. Here, Π^{ca} denotes the discounted sum of single period profits from capelin; and δ^{ca} is the discount factor of the capelin owner. Notice that even though the stock level of capelin does not enter the profit function above, it does so in the constraints.

Joint management

Under sole ownership, the objective is to maximise the sum of the single period discounted profits from the two fisheries. Thus, the problem of the sole owner is to maximise

$$(13) \qquad \Pi := \Pi^{co} + \Pi^{ca}$$

with respect to the effort levels exerted on the two species and their stock levels, subject to equations (5) and (7) above. In addition, it is understood that the obvious nonnegativity constraints are satisfied. Here, Π denotes the discounted sum of single period profits from both cod and capelin.

Cod only fishery

The aim here is to explore questions such as, is there a relative price of cod or capelin at which it is economically sensible to harvest only one of them? *A priori*, this question is relevant only in the case of a cod only scenario. The capelin only scenario is bound to give an inferior outcome relative to the case where both fisheries are active because of two reasons. First, no harvesting of cod would imply heavy predation on capelin, *ceteris paribus*. Second, capelin is the less valuable of the two species. Consequently, we refrain from analysing a capelin only scenario.

On the equilibrium solutions identified

We set out to identify Nash non-cooperative and sole ownership equilibrium solutions for the model outlined above. A Nash non-cooperative equilibrium in this context is a pair of strategy profiles, $\{(e_{ca}^*),(e_{co}^*,n_{co}^*)\}$, such that no player will find it in his best interest to change strategy given that his opponent keeps to his. On the other hand, an example of a joint management equilibrium is the outcome of the maximisation of equation (13) under the relevant conditions.

Relying on the works of Nash (1950, 1951) and Rosen (1965), it is taken for granted that Nash equilibrium solutions exist in the 2-person concave game we formulate[8]. In addition, Cavazzuti and Flåm (1992) show that if along the equilibrium profile players face the same shadow prices then the equilibrium tends to be unique.

---

[8] Strict concavity is ensured in the objective functional of players through the way cost functions are modelled.

It should be noted that the solutions we compute in the non-cooperative scenario do not subscribe fully to the customary open loop solution concept derived from control theory. Unlike here where agents impact on their rivals stock indirectly through their choice of effort level, in the customary open loop solutions, agents are expected to directly control their rival's stock once the rival has committed to a given profile of actions.

Table 1. Parameter values used in the model

Biological parameters	Comments/source
$S^{co} = 0.81$	Standard for cod
$S^{ca} = 0.535$	Eide & Flaaten (1992)
$\chi = 1.5$ per mill. tonnes	Chosen to give biomass of 5 mill. without fishing
$\gamma = 1.0$ per mill. tonnes	"
$R^{ca} = 4.32$ mill. tonnes	cf. Digernes (1980)
$E = 0.5$ mill. tonnes	Tjelmeland (1982)
$\beta = 1.2$	Choice as in Moxnes (1992)
$k_1 = 1.235$	"
$k_2 = 0.6$	"
$\tilde{\beta}_{prey} = 4.467$	"
$D^{max}_{prey} = 1.5$	"
$GW_{ao} = 0.2, 0.21, 0.25, 0.3, 0.35, 0.45, 0.562,$ $0.744, 0.826, 1.0, 1.4, 1.4, 1.45, 1.45, 1.45, 1.5)$	Based on data in Moxnes (1992)
$n^{co}_{a,0} = (0.46, 0.337, 0.298, 0.223, 0.117, 0.061,$ $0.033, 0.009, 0.009, 0.009, 0.009, 0.009,$ $0.009, 0.009, 0.009)$	Average of initial numbers (in billions) from 1984 - 91 reported in Table 3.12 of the ICES (1992)
$n^{co}_{a,0} = (500, 240, 163, 78, 38)$	Choice based on data in IMR (1994) in billions.
$p_a = (0,0,0,0,0,0,0,1,1,1,1,1,1,1,1)$	Knife-edge selectivity applied
$W^{ca}_a = (0.012, 0.018, 0.021, 0.022)$	Moxnes (1992) in kg.
$W^{co}_{a,0} = (0.3, 0.6, 1, 1.4, 1.83, 2.26, 3.27, 4.27, 5.78,$ $7.96, 9.79, 11.53, 13.84, 15.24, 16.34)$	ICES (1992) in kg.
Economic parameters	
$p^{co} = $ NOK 6.78 per kg	Sumaila (1995)
$p^{ca} = $ NOK 0.6 per kg	Moxnes (1992)
$K^{co} = $ NOK 210 mill.	Kjelby (1993)
$K^{ca} = $ NOK 10 mill.	Based on data in Flåm (1994)
Interest rate = 7%	Recommended by the Ministry of Finance, Norway
Technological parameters	
$q^{ca} = 0.175$	Based on data in Moxnes (1992)
$q^{co} = 0.068$	Sumaila (1994)

Numerical results

To solve the model, we apply a numerical procedure whose mathematical formulation is developed in Flåm (1993), and applied to solve a single species model in Sumaila (1995). The detailed problem-specific problem is given in an appendix. The parameters used for the computations are given in Table 1 above. The data comes from a number of sources including, the IMR (1994), ICES (1992 and 1996), Kjelby (1993), Moxnes (1992), Flåm (1994), and Digernes (1980). Note that for the sake of scaling, a fleet size of 10 trawlers and 10 purse seiners are used as the unit of fishing effort. The simulation commences January 1, 1996 and runs for the next 20 years until the year 2016.

Figure 3: Weight vs. Age
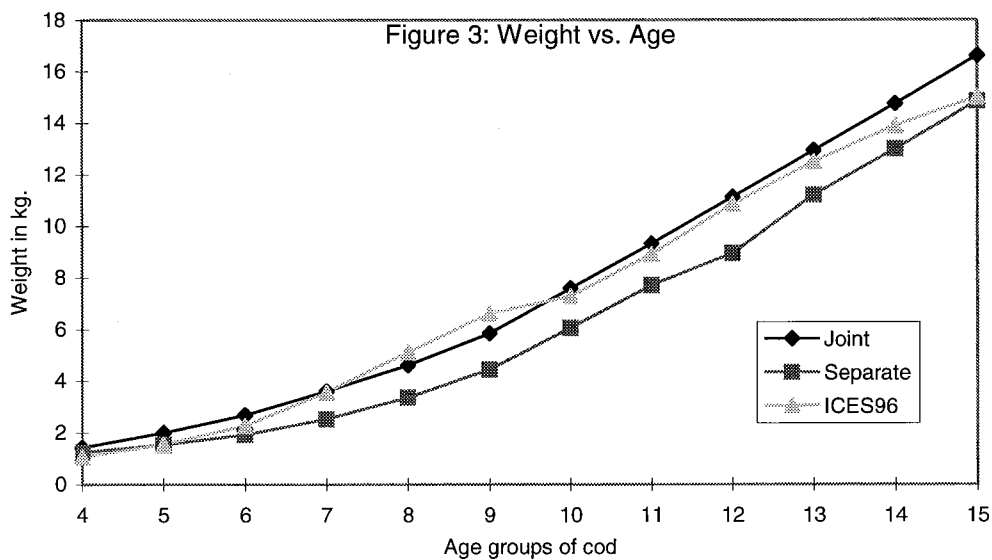
The results

A plot of *weight versus age* of cod for a typical yearclass given by our model under joint and separate management is given in Figure 3 above. In addition, a plot of the weight of the

different age groups of cod reported in ICES (1996) is given on the same graph. We see from the graph that (i) joint management produces cod with the most weight, especially for older age groups, (ii) non-cooperation produces cod with the least weight, and (iii) current ICES estimates of the weight of cod lies in between those for the joint and separate management cases, which shows that the current effort at joint management of the two species is yielding some positive results, even though short of what our model predicts.

Payoffs under the different management regimes

Table 2 below presents the payoffs to the agents under the different management regimes. Column 2 of the Table gives the base case outcomes, while columns 3 to 5 present the outcomes from (*ceteris paribus*) sensitivity analysis. The following can be deduced from the Table.

- From column 2, we see that, as expected the best economic result of NOK 67.19 billion (capelin contribution 4%) is achieved when both species are harvested under joint management. On the other hand, the worst economic result of NOK 54.44 billion (capelin contribution 11%) is obtained when the species are harvested under separate management. A situation where only the cod fishery is active yields a result (NOK 65.58 billion) better than that obtained under separate management but worse than that under joint management.

  The economic loss stemming from the externalities that arise due to the natural interactions between the two species is significant, reaching upto NOK 12.75 billion, or about 23% of what is achievable under separate management. The higher benefits

17

Table 2. Payoffs from cod and capelin under the different management regimes (in billion NOK)

Management Regime		Base case	25% increase in price		25% increase in cost		Increase (0.935 to 0.99) in DF[1]	
			cod	capelin	cod	capelin	cod	capelin
Joint	cod	64.42	84.73	64.31	59.27	64.46	-	-
	capelin	2.77	2.83	3.93	2.68	2.71	-	-
	total	**67.19**	**87.56**	**68.24**	**59.27**	**67.17**	--	-
Separate	cod	48.56	62.42	46.89	44.80	50.44	76.86	44.92
	capelin	5.88	6.59	7.78	5.78	5.63	7.31	9.60
	total	**54.44**	**69.01**	**54.67**	**50.58**	**56.07**	**84.17**	**54.52**
Cod only	-	65.58	85.98		60.48		103.70	

---

[1] DF denotes discount factor.

accruable under joint management is due to a sensible allocation of the prey stock between predation and harvesting: A good part of the capelin stock is not harvested in the joint management case but rather left for the cod species to feed on. For instance, a total of only 7.58 million tonnes of capelin is harvested under joint management, compare this with the 15.93 million tonnes harvested under separate management, and the point made here will immediately become clear.

- An increase (decrease) in the price (harvesting cost) of cod results in an increase in the respective payoffs from cod and capelin under both separate and joint management (see column 3 and 5). This is because an increase (decrease) in the price (harvesting cost) of cod results in higher fishing mortality on cod, which in turn releases more capelin for harvesting.

- A positive change in the price of capelin leads to a decrease in the payoff to the cod owner, and an increase in the payoff from capelin under both separate and joint management (column 4). Such an increase in price makes it economically sensible to harvest more capelin thereby making less capelin available for predation. The opposite results are obtained with an increase in the harvesting cost of capelin. The interesting point here is that under separate management, the gain in payoff by the cod owner is higher than the loss in payoff to the capelin owner, so that overall, an increase in the cost of harvesting capelin by 25% leads to an increase in the total payoff to the fishing community.

- An increase in the discount factor faced by one or the other of the two fisheries leads both to an increase in the total payoff from the resource, and the share or contribution of

the fishery facing the increase. This happens irrespective of the management regime under consideration. Also, allowing only the cod fishery to be active tend to be more plausible as the cod fishery faces relatively higher discount factor than the capelin fishery.

Stock sizes, catches, and predation level

- Generally, the computed outcomes confirm the results of Fischer and Mirman (1992): From Table 3 we see that, joint management leads to a lower average annual catch of capelin (0.38 million tonnes) and a higher average annual catch of cod (1.24 million tonnes) compared to the separate management case at 0.8 and 0.94 million tonnes, respectively. Also, the average annual standing biomass of 3 and 4 year-old capelin turns out to be higher under joint management (1.55 million tonnes) than under separate management (0.9 million tonnes), while the average annual standing biomass of cod is lower under joint management (2.23 million tonnes) than under separate management (2.62 million tonnes). A probable explanation of the latter result is that the higher growth rate of cod implied by joint management means that sustainable catches of cod are achievable at a lower standing biomass.

Table 3. Average annual standing biomass and yield under the two management regimes (in million tonnes)

Management Regime	cod		capelin	
	stock	harvest	stock	harvest
Joint	2.23	1.24	1.55	0.38
Separate	2.62	0.94	0.90	0.80

- Table 4 below presents the total capelin harvest and predation for increased prices, costs, and discount factors. This Table reveals that under separate management, (i) an increase in the price of cod or a decrease in its harvest cost, leads to an increase in the harvest of capelin and a decrease in predation by cod; (ii) an increase in the price of capelin or a decrease in the cost of harvesting capelin also leads to a decrease in predation and an increase in harvest of capelin. It can also be seen from Table 4 that an increase in the discount factor of either fishery results in an increase in the harvest, and a decrease in the predation of capelin. The intuition behind these results is already given under section 4.1.1.

Table 4. Effect of changes in economic parameters on capelin harvest and predation[1]

Management Regime		Base Case (million tonnes)	25% increase in price		25% increase in cost		Increase (0.935 to 0.99) in DF	
			cod	capelin	cod	capelin	cod	capelin
Joint	Harvest	7.58	7.73	9.10	7.48	7.34	-	-
	Predation	10.31	9.50	10.40	10.31	10.42	-	-
Separate	Harvest	15.93	18.97	16.90	15.17	15.48	22.37	18.14
	Predation	7.45	4.81	6.87	7.96	7.65	3.12	6.35

[1] Table 3 and 4 do not include the cod only scenario because the purpose here is to reveal the trade-off between harvest and predation in the separate and joint management regimes.

Concluding remarks

This study shows that there will be an economic loss if cod and capelin are exploited as if there were no biological interaction between them. Allowing for the fact that modelling and computations are exercises in successive approximations, this loss is computed to be nearly 25% of what is achievable if this interaction is neglected. In the summer of 1992 and the winter of 1993, 0.2 and 0.57 million tonnes of capelin were landed, respectively, from the Barents Sea (IMR, 1994, Table 1.5.1). This means that a total of 0.77 million tonnes of capelin was landed in the 1992/93 fishing year. Our model gives an average annual catch of 0.8 and 0.38 million tonnes of capelin, respectively, under non-cooperation and cooperation: an indication that current management practice does better than what would be achieved under non-cooperation, but clearly, it does not leave enough capelin to be "fished" by cod, as would be necessary under cooperative management.

Two other studies (Flaaten, 1988 and Eide and Flaaten, 1992) come to similar conclusions. This would tend to make a strong case for a severe curtailment of the capelin fishery in the Barents Sea. We need, however, to highlight the fact that the biological models applied in these studies do not perfectly capture the predator-prey relationships between cod and capelin, not to mention the fact that these studies are partial in the sense that they do not include all the important predators (seals and whales) and preys in the habitat. In addition, this study is deterministic and thus, cannot be expected to give a perfect picture of the world under investigation. Nevertheless, the results of this paper should give the relevant fisheries managers some food for thought.

APPENDIX: The algorithm

The reader is referred to Sumaila (1995) which explains how the equations below are derived and presents a single species application of the method.

Lagrangian function under cooperation

(14)

$$L(n^{co}, n^{ca}, e^{co}, e^{ca}, y^{co}, y^{ca}) = \Pi^{co}\left(n^{co}, n^{ca}, e^{co}\right) + \Pi^{ca}\left(e^{ca}\right)$$

$$+ \sum_{t=1}^{T}\begin{bmatrix} y_{0,t}^{co}\left(f(B_{t-1}^{co} - n_{0,t}^{co}\right)^{-} \\ + \sum_{a=1}^{A-1} y_{a,t}^{co}(s^{co}n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})^{-} \\ + y_{A,t}^{co}(s^{co}n_{A,t-1}^{co} + s^{co}n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})^{-} \end{bmatrix} + \sum_{t=1}^{T}\begin{bmatrix} y_{1,t}^{ca}\left(R^{ca} - n_{1,t}^{ca}\right)^{-} \\ + y_{2,t}^{ca}(s^{ca}n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})^{-} \\ + y_{3,t}^{ca}(s^{ca}n_{2,t-1}^{ca} - n_{3,t}^{ca} - P_{3,t}^{ca} - h_{3,t}^{ca})^{-} \\ + y_{4,t}^{ca}(s^{ca}n_{3,t-1}^{ca} - n_{4,t}^{ca} - P_{4,t}^{ca} - h_{4,t}^{ca} - E)^{-} \end{bmatrix}$$

Lagrangian functions under non-cooperation, one for each owner

(15) $$L_{co}(n^{co}, e^{co}, y^{co}) = \Pi^{co}\left(n^{co}, n^{ca}, e^{co}\right) + \sum_{t=1}^{T}\begin{bmatrix} y_{0,t}^{co}\left(f(B_{t-1}^{co} - n_{0,t}^{co}\right)^{-} \\ + \sum_{a=1}^{A-1} y_{a,t}^{co}(s^{co}n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})^{-} \\ + y_{A,t}^{co}(s^{co}n_{A,t-1}^{co} + s^{co}n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})^{-} \end{bmatrix}$$

(16) $$L_{ca}(n^{ca}, e^{ca}, y^{ca}) = \Pi^{ca}\left(e^{ca}\right) + \sum_{t=1}^{T}\begin{bmatrix} y_{1,t}^{ca}\left(R^{ca} - n_{1,t}^{ca}\right)^{-} \\ + y_{2,t}^{ca}(s^{ca}n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})^{-} \\ + y_{3,t}^{ca}(s^{ca}n_{2,t-1}^{ca} - n_{3,t}^{ca} - P_{3,t}^{ca} - h_{3,t}^{ca})^{-} \\ + y_{4,t}^{ca}(s^{ca}n_{3,t-1}^{ca} - n_{4,t}^{ca} - P_{4,t}^{ca} - h_{4,t}^{ca} - E)^{-} \end{bmatrix}$$

Cod effort adjustment under cooperation

$$\frac{\partial L(.)}{\partial e_t^{co}} = \delta_{co}^t p^{co} \left(\sum_a w_{a,t}^{co}(D_{prey}) q_a^{co} n_{a,t}^{co} - \psi^{co} e_t^{co^{0.01}} \right)$$

$$+ \sum_{a=1}^{A-1} y_{a,t}^{co} H(s^{co} n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})(-q_a^{co} n_{a,t}^{co})$$

$$(17) \qquad + y_{A,t}^{co} H(s^{co} n_{A,t-1}^{co} + s^{co} n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})(-q_A^{co} n_{A,t}^{co})$$

$$+ \sum_{a=3}^{4} y_{a,t}^{ca} \left(\frac{\partial \Phi^{ca^-}}{\partial n_{a,t}^{co}} \right) \left(\frac{\partial n_{a,t}^{co}}{e_t^{co}} \right)$$

Cod effort adjustment under non-cooperation

$$\frac{\partial L(.)}{\partial e_t^{co}} = \delta_{co}^t p^{co} \left(\sum_a w_{a,t}^{co}(D_{prey}) q_a^{co} n_{a,t}^{co} - \psi^{co} e_t^{co^{0.01}} \right)$$

$$(18) \qquad + \sum_{a=1}^{A-1} y_{a,t}^{co} H(s^{co} n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})(-q_a^{co} n_{a,t}^{co})$$

$$+ y_{A,t}^{co} H(s^{co} n_{A,t-1}^{co} + s^{co} n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})(-q_A^{co} n_{A,t}^{co})$$

Capelin effort adjustment under cooperation and non-cooperation

$$\frac{\partial L(.)}{\partial e_t^{ca}} = \delta_{ca}^t p^{ca} \left(\sum_a w_a^{ca} q_a^{ca} - \psi^{ca} e_t^{ca^{0.01}} \right)$$

$$(19) \qquad + y_{3,t}^{ca} H(s^{ca} n_{2,t-1}^{ca} - n_{3,t}^{ca} - h_{3,t}^{ca} - P_{3,t}^{ca})(-q_3^{ca})$$

$$+ y_{4t}^{ca} H(s^{ca} n_{3,t-1}^{ca} - n_{4,t}^{ca} - h_{4,t}^{ca} - P_{4,t}^{ca} - E)(-q_4^{ca})$$

Cod multiplier adjustment under cooperation and non-cooperation

$$(20) \qquad \frac{\partial L(.)}{\partial y_{0,t}^{co}} = -H(f(B_{t-1}^{co} - n_{0,t}^{co})(B_{t-1}^{co} - n_{0,t}^{co})$$

$$(21) \qquad \frac{\partial L(.)}{\partial y_{a,t}^{co}} = -H(s^{co} n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})(s^{co} n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co}) \ \forall \ 0 < a < A$$

$$(22) \qquad \frac{\partial L(.)}{\partial y_{A,t}^{co}} = -H(s^{co} n_{A,t-1}^{co} + s^{co} n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})(s^{co} n_{A,t-1}^{co} + s^{co} n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})$$

Capelin multiplier adjustment under cooperation and non-cooperation

$$(23) \qquad \frac{\partial L(.)}{\partial y_{1,t}^{ca}} = -H(R^{ca} - n_{1,t}^{co})(R^{ca} - n_{1,t}^{ca})$$

$$(24) \qquad \frac{\partial L(.)}{\partial y_{2,t}^{ca}} = -H(s^{ca} n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})(s^{ca} n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})$$

$$(25) \qquad \frac{\partial L(.)}{\partial y_{3,t}^{ca}} = -H(s^{ca} n_{2,t-1}^{ca} - n_{3,t}^{ca} - h_{3,t}^{ca} - P_{3,t}^{ca})(s^{ca} n_{2,t-1}^{ca} - n_{3,t}^{ca} - h_{3,t}^{ca} - P_{3,t}^{ca})$$

$$(26) \qquad \frac{\partial L(.)}{\partial y_{4,t}^{ca}} = -H(s^{ca} n_{3,t-1}^{ca} - n_{4,t}^{ca} - h_{4,t}^{ca} - P_{4,t}^{ca} - E)(s^{ca} n_{3,t-1}^{ca} - n_{4,t}^{ca} - h_{4,t}^{ca} - P_{4,t}^{ca} - E)$$

Cod stock adjustment under cooperation and non-cooperation

$$
\begin{aligned}
(27) \qquad y_{o,t}^{co} \frac{\partial \Phi^{co^-}(.)}{\partial n_{o,t}^{co}} &= y_{o,t}^{co} H(f(B_{t-1}^{co}) - n_{0,t}^{co}) \frac{\partial f(B_{t-1}^{co})}{\partial n_{o,t}^{co}} \\
&\quad - y_{o,t}^{co} H(f(B_{t-1}^{co}) - n_{0,t}^{co}) \\
&\quad + y_{1,t+1}^{co} H(s^{co} n_{0,t}^{co} - n_{1,t+1}^{co}) s^{co}
\end{aligned}
$$

$$
\begin{aligned}
(28) \qquad y_{o,t}^{co} \frac{\partial \Phi^{co^-}(.)}{\partial n_{a,t}^{co}} &= \frac{\partial \Pi^{co}}{\partial n_{a,t}^{co}} + y_{o,t}^{co} H(f(B_{t-1}^{co}) - n_{0,t}^{co}) \frac{\partial f(B_{t-1}^{co})}{\partial n_{o,t}^{co}} \\
&\quad + y_{o,t}^{co} H(s^{co} n_{a-1,t-1}^{co} - n_{a,t}^{co} - h_{a,t}^{co})(-1 - \sum_p q_a^{co} e_t^{co}) \\
&\quad + y_{a+1,t+1}^{co} H(s^{co} n_{a,t}^{co} - n_{a+1,t+1}^{co} - h_{a+1,t+1}^{co}) s^{co} \qquad \forall\ 0 < a < A - 1
\end{aligned}
$$

$$
\begin{aligned}
(29) \qquad y_{o,t}^{co} \frac{\partial \Phi^{co^-}(.)}{\partial n_{A-1,t}^{co}} &= \frac{\partial \Pi^{co}}{\partial n_{A-1,t}^{co}} + y_{o,t+1}^{co} H(f(B_t^{co}) - n_{0,t+1}^{co}) \frac{\partial f(B_t^{co})}{\partial n_{A,t}^{co}} \\
&\quad + y_{A-1,t}^{co} H(s^{co} n_{A-2,t-1}^{co} - n_{A-1,t}^{co} - h_{A-1,t}^{co})(-1 - q_{A-1}^{co} e_t^{co}) \\
&\quad + y_{A,t+1}^{co} H(s^{co} n_{A,t}^{co} + s^{co} n_{A-1,t}^{co} - n_{A,t+1}^{co} - h_{A,t+1}^{co}) s^{co}
\end{aligned}
$$

$$y_{A,t}^{co} \frac{\partial \Phi^{co^-}(.)}{\partial n_{A,t}^{co}} = \frac{\partial \Pi^{co}}{\partial n_{A,t}^{co}} + y_{o,t+1}^{co} H(f(B_t^{co}) - n_{0,t+1}^{co}) \frac{\partial f(B_t^{co})}{\partial n_{A,t}^{co}}$$

$$(30) \qquad + y_{A,t+1}^{co} H(s^{co} n_{A,t}^{co} + s^{co} n_{A-1,t}^{co} - n_{A,t+1}^{co} - h_{A,t+1}^{co}) s^{co}$$

$$+ y_{A,t}^{co} H(s^{co} n_{A,t-1}^{co} + s^{co} n_{A-1,t-1}^{co} - n_{A,t}^{co} - h_{A,t}^{co})(-1 - q_A^{co} e_t^{co})$$

Capelin stock adjustment under cooperation

$$(31) \qquad y_{1,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{o,t}^{ca}} = -y_{1,t}^{ca} H(R^{ca} - n_{1,t}^{ca})$$

$$+ y_{2,t+1}^{ca} H(s^{ca} n_{,t}^{ca} - n_{2,t+1}^{ca} - n_{2,t+1}^{ca}) s^{ca}$$

$$(32) \qquad y_{2,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{2,t}^{ca}} = y_{2,t}^{ca} H(s^{ca} n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})(-1 - \frac{\partial P_{2,t}^{ca}}{\partial n_{2,t}^{ca}})$$

$$+ y_{3,t+1}^{ca} H(s^{ca} n_{2,t}^{ca} - n_{3,t+1}^{ca} - h_{3,t+1}^{ca} - P_{3,t+1}^{ca}) s^{ca}$$

$$(33) \qquad y_{3,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{3,t}^{ca}} = \frac{\partial \Pi^{c0}}{\partial n_{3,t}^{ca}} + y_{3,t}^{ca} H(s^{ca} n_{2,t-1}^{ca} - n_{3,t}^{ca} - P_{3,t}^{ca} - h_{3,t}^{ca})(-1 - \frac{\partial P_{3,t}^{ca}}{\partial n_{3,t}^{ca}})$$

$$+ y_{4,t+1}^{ca} H(s^{ca} n_{3,t}^{ca} - n_{4,t+1}^{ca} - h_{4,t+1}^{ca} - P_{4,t+1}^{ca} - E) s^{ca}$$

$$(34) \qquad y_{4,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{4,t}^{ca}} = \frac{\partial \Pi^{co}}{\partial n_{4,t}^{ca}} + y_{4,t}^{ca} H(s^{ca} n_{3,t-1}^{ca} - n_{4,t}^{ca} - P_{4,t}^{ca} - h_{4,t}^{ca} - E)(-1 - \frac{\partial P_{4,t}^{ca}}{\partial n_{4,t}^{ca}})$$

Capelin stock adjustment under non-cooperation

$$(35) \qquad y_{o,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{o,t}^{ca}} = -y_{1,t}^{ca} H(R^{ca} - n_{1,t}^{ca})$$

$$+ y_{2,t+1}^{ca} H(s^{ca} n_{,t}^{ca} - n_{2,t+1}^{ca} - n_{2,t+1}^{ca}) s^{ca}$$

$$(36) \quad y_{2,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{2,t}^{ca}} = y_{2,t}^{ca} H(s^{ca} n_{1,t-1}^{ca} - n_{2,t}^{ca} - P_{2,t}^{ca})(-1 - \frac{\partial P_{2,t}^{ca}}{\partial n_{2,t}^{ca}})$$

$$+ y_{3,t+1}^{ca} H(s^{ca} n_{2,t}^{ca} - n_{3,t+1}^{ca} - h_{3,t+1}^{ca} - P_{3,t+1}^{ca}) s^{ca}$$

$$(37) \quad y_{3,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{3,t}^{ca}} = y_{3,t}^{ca} H(s^{ca} n_{2,t-1}^{ca} - n_{3,t}^{ca} - P_{3,t}^{ca} - h_{3,t}^{ca})(-1 - \frac{\partial P_{3,t}^{ca}}{\partial n_{3,t}^{ca}})$$

$$+ y_{4,t+1}^{ca} H(s^{ca} n_{3,t}^{ca} - n_{4,t+1}^{ca} - h_{4,t+1}^{ca} - P_{4,t+1}^{ca} - E) s^{ca}$$

$$(38) \quad y_{4,t}^{ca} \frac{\partial \Phi^{ca^-}(.)}{\partial n_{4,t}^{ca}} = y_{4,t}^{ca} H(s^{ca} n_{3,t-1}^{ca} - n_{4,t}^{ca} - P_{4,t}^{ca} - h_{4,t}^{ca} - E)(-1 - \frac{\partial P_{4,t}^{ca}}{\partial n_{4,t}^{ca}})$$

REFERENCE LIST

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

Cavazzuti, E. and S.D. Flåm 1992. Evolution and selected Nash equilibria. In E. Giannessi (ed.): *Nonsmooth Optimization Method and Application. London:* Gordon and Breach.

Clark, C.W. and G.P. Kirkwood 1979. Bioeconomic model of the Gulf of Carpentaria prawn fishery. *Journal of the Fisheries Research Board of Canada* 36: 1304-1312.

Digernes, T. 1980. Matematisk modellering av fiskebestander (mathematical modelling of fish stocks). Institutt for Atomenergi, Report no. ESS-27 (in Norwegian).

Eide, A. and Flaaten, O. 1992. Bioeconomic modelling of the Barents Sea fisheries. Paper presented at the VIth Conference of the Intern. Inst.of fish. Econ. and Trade, Session no. 3, part A, Paris, July 6-9, 1992.

Fischer, R.D. and Mirman, L.J. 1992. Strategic dynamic interaction: Fish wars. *Journal of Dynamics and Control.* 16: 267-287. North-Holland.

Flaaten, O. and Armstrong, C. 1991. Non-cooperative and cooperative management of transboundary interdependent natural resources. University of Tromsø, Norwegian College of Fishery Science, *Working Paper.*

Flaaten, O. 1988. *The economics of multispecies harvesting - theory and application to the Barents Sea fisheries.* Studies in Contemporary Economics. Berlin - Tokyo. Springer-Verlag.

Flåm, S.D. 1994. Kor mykje er dei norske sildefiskeria verdt? (What is the value of the Norwegian herring fishery?) *Sosialøkonomen* 48(4): 2-5. (in Norwegian).

Flåm, S.D. 1993. Path to constrained Nash equilibria. *Applied Mathematics and Optimisation.* 27: 275-289.

Hamre, J. and Tjelmeland, S. 1982. Sustainable yield estimates of the Barents Sea capelin stock. *International Council for the Exploration of the Sea*, Copenhagen.

Hannesson, R. 1983. Optimal harvesting of ecologically interdependent fish species. *Journal of Environmental Economics and management. 10: 329-345.*

Holling, C.S. 1965. The functional response of predators to prey density and its role in mimicry and population regulations. *Mem. Ent. Soc. Can.* 45: 1-60.

ICES, 1992. Report of the Arctic Fisheries Working Group, International Council for Exploration of Sea, Copenhagen.

ICES, 1996. Report of the Arctic Fisheries Working Group, International Council for Exploration of Sea, Copenhagen.

IMR, 1994. Ressursoversikt: Fisken og Havet (Fish and the Sea), Institute of Marine Research, Særnummer 1.

Kjelby, T. (1993): Det norske torskefiskeriet som nasjonalformue. SEFOS Notat 90 (in Norwegian).

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

Moxnes, (1992): Multispecies management under uncertainty. SNF (Centre for Research in Economics and Business Administration, Norwegian School of Business and Administration, Bergen) Report N0. 95/1992. 34 p.

Munro, G. R. (1979): The optimal management of transboundary renewable resources. *Canadian Journal of Economics* 12(8): 355-376.

Nash, J.F. 1950. Equilibrium points in n-person games. *Proceedings of the National Academy of Science*, USA., 36:48-49.

Nash, J.F. 1951. Non-cooperative games. *Annals of Mathematics*, 54:286-295.

Quirk, J.P. and Smith V.L. 1977. Dynamic economic models of fishing, in "Economics of fisheries management: A Symposium" (A.D. Scott, Ed.), 3-32.

Rosen, J.B. 1965. Existence and uniqueness of equilibrium points for concave n-person games. *Econometrica*, 33:520-534.

Sivert, W. and Smith, W.R. 1977. Optimal exploitation of a multispecies community. *Math. Biosci.* 33: 121-134.

Sumaila, U.R. 1995. Irreversible capital investment in a two-stage bimatrix fishery game model. *Marine Resource Economics* 10 263-283.

Sumaila, U.R. 1994. A two agent model for the Arcto-Norwegian cod. Dept. of Economics, University of Bergen, *Working paper* No. 0694. 18 p.

Tjelmeland, S.1990. MULTSIMP: a simplified multispecies model for the Barents Sea. MULTSPEC support papers, Institute of Marine Research, Bergen.

Recent Working Papers

WP 1995: 3   ANGELSEN, Arild and Odd-Helge Fjeldstad
Land reforms and land degradation in Tanzania: Alternative economic approaches. Bergen, July 1995, 38 pp.

WP 1995: 4   FJELDSTAD, Odd-Helge
Taxation and tax reforms in Tanzania: A survey. Bergen, November 1995, 35 pp.

WP 1995: 5   FJELDSTAD, Odd-Helge
Valued-added taxation in Tanzania? Bergen, November 1995, 27 pp.

WP 1996: 1   STOKKE, Hugo
Institutional approaches to the study of international organisation. Bergen, February 1996, 23 pp.

WP 1996: 2   TJOMSLAND, Marit
A discussion of three theoretical approaches to modernity: Understanding modernity as a globalising phenomenon. Bergen, July 1996, 24 pp.

WP 1996: 3   KNUDSEN, Are J. and Kate Halvorsen
Income-generating programmes in Pakistan and Malawi: A comparative review. Bergen, August 1996.

WP 1996:4   FJELDSTAD, Odd-Helge
Bistand og næringsutvikling. Noen kommentarer til St. meld. nr. 19 (1995-96). Bergen, august 1996, 17 s.

WP 1996: 5   RAKNER, Lise and Tor Skålnes
Political institutions and economic reform: Zambia and South Africa in comparative context. Bergen, September 1996, 44 pp.

WP 1996: 6   RAKNER, Lise
Rational choice and the problem of institutions. A discussion of rational choice institutionalism and its application by Robert Bates. Bergen, September 1996, 31 pp.

WP 1996: 7   ARIFIN, Bustanul
Economic analysis of land degradation in Indonesian upland. Bergen, September 1996, 20 pp.

WP 1996: 8   PAUSEWANG, Siegfried
"Eneweyay" (Let's Discuss). Bergen, September 1996.

WP 1996: 9   ANGELSEN, Arild
Deforestation: Population or market driven? Different approaches in modelling agricultural expansion. Bergen, September 1996, 30 pp.

WP 1996: 10   ANGELSEN, Arild and Richard Culas
Debt and deforestation: A tenuous link. Bergen, September 1996, 29 pp.

WP 1996: 11   KNUDSEN, Are J.
Deforestation and entrepreneurship in the North West Frontier Province, Pakistan. Bergen, October 1996, 22 pp.

WP 1996: 12   NORDÅS, Hildegunn Kyvik
Trade and growth with static and dynamic economies of scale. Bergen, November 1966, 36 pp.

WP 19996: 13   LØNNING, Dag Jørund
Dealing with the good and the evil. Introducing morality as an anthropological concern. Bergen, December 1996, 27 pp.

WP 1996: 14   FJELDSTAD, Odd Helge
Tax evasion and corruption in local governments in Tanzania: Alternative economic approaches. Bergen, December 1996, 33 pp.