Cannibalism and the optimal sharing of the North-East Atlantic cod stock: A computation model

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WP 1998: 4

Working Paper
Chr. Michelsen Institute
Development Studies and Human Rights
Bergen Norway

ISSN 0804-3639

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Bergen, February 1998. 27 pp.

Summary:

This paper shows how intra-stock relations, such as cannibalism and growth enhancement, define the optimal sharing of a fish resource between heterogeneous harvesting agents. The sharing of resources between different vessel groups is often left for political decision making. Nonetheless, such decisions may have both biological and economic consequences. This becomes quite clear when different harvesting groups exploit different sections (age groups) of a stock that has intra-stock interactions in the form of cannibalism. A two-agent bioeconomic model with cannibalism is developed and used to determine (i) optimal annual harvest sizes (TACS) for cod, and (ii) the optimal proportion of the TAC that should be harvested by the trawler and coastal fleets. Applying biological and economic data in a numerical procedure, and comparing the results obtained to previous studies, it is shown that the presence of cannibalism has a significant impact on who should take what proportion of the TAC, and hence, the standing stock size and discounted economic rent achievable. In sharp contrast to other studies, we find that the optimal harvest requires that both trawlers and coastal vessels should harvest the fish resource. In addition, the results indicate that from a bioeconomic perspective, the existing trawler fleet's harvest share in the cod fishery is too high.

Indexing terms:

Bioeconomics
Cooperatives
Fishery resources
Cod
Harvesting
Norway
Russia

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INTRODUCTION

Over the years fisheries managers in many countries have come to accept the concept of bioeconomic management of fish resources. The application of bioeconomics has, however, if at all, usually been limited to the determination of total allowable catch (TAC), while the sharing of the TAC between heterogeneous fisher groups has been thought to be a political issue. Hence, the fact that different fisher groups harvest upon different sections of fish stocks, and thereby have different effects upon both stock growth and the economics of the fishery, are not taken into account. That is, the political determination of harvest shares has bioeconomic effects, for instance, in the shape of reduced payoffs from the fishery, or even extinction. The bioeconomic losses could become quite serious when there is cannibalistic interaction between sub-stocks within a single species. In this paper we study such cannibalistic interaction between two sub-stocks that are fished upon by two separate vessel groups. We show how, in the same manner that bioeconomics has become an important tool in multispecies management, a similar approach can be used profitably to manage species with intra-stock interaction.

We develop a bioeconomic model in order to study optimal harvest shares for two vessel groups, namely, trawlers and coastal vessels, operating in the environment described in the preceding paragraph. This is done using a cooperative approach to the issue of sharing the harvest of the North-East Atlantic Cod stock. This stock is jointly managed by Russia and Norway, the former country relying solely upon trawler technology. These two countries get together annually to decide the total allowable catch (TAC), and their respective shares of this harvest. Furthermore, Norway must determine how to divide the Norwegian share of the TAC between heterogeneous fisher groups; that is, trawlers and coastal vessels, that harvest upon different sections of the stock. In this paper we determine the joint (cooperative) and separate (non-cooperative) solutions to this resource sharing problem in a cannibalistic interaction model.

Spulber (1985) introduces the problem of using lumped parameter models for non-selective harvesting decisions in multicohort stocks. He shows how sustainable harvesting may lead to extinction, if the total harvest is made up of excessive harvesting of recruits or spawners. His analysis is purely theoretical, illustrating the problem by allowing a sole owner to harvest either selectively or non-selectively. We apply the theory to a two agent situation found in an actual fishery. Sumaila (1997) presents a multicohort model for the analysis of the management of the North-East Atlantic Cod stock. However, this paper does not allow for cannibalistic behaviour which we present (and which Eide (1993) shows to be an important explanatory function of changes regarding the North-East Atlantic Cod stock). Armstrong (1997) studies cannibalism and the sharing of harvests, but does not allow for optimal harvesting in the build-up phase of the stock, such as is allowed in the current model. Klieve and MacAulay (1993) analyse the Southern Bluefin Tuna fishery, where Japanese and Australian fishers harvest on different sections of the stock. Klieve and MacAulay (op.cit.) define different harvest strategies for the two countries with respect to the choice of age at harvest. Applying the Nash bargaining solution concept (see Munro, 1979), the authors determine which strategy combinations give the highest joint payoff to the players. This approach differs from ours in that we do not limit our study to the cooperative solution given by Nash (1953), which in itself gives preference to one country when there is asymmetry between the countries. Furthermore, we assume that the harvest strategies of the two vessel groups are determined by their existing technologies and their respective fishing grounds. Hence we can determine overall optimal sharing of the resource, after deciding the weights that should be given to the two party's preferences.

Comparisons with earlier studies where cannibalism is not included, show that cannibalistic interaction results in large economic losses (see Sumaila, 1997). The incorporation of cannibalistic behavior also affects how the annual harvest should be shared optimally between the coastal and trawler fleets. We find that a shared harvest is bioeconomically superior to a corner solution, in sharp contrast to earlier studies. Furthermore, we find that the existing allocation rule applied by managers of the North East Atlantic cod gives a sub-optimally high share of the total harvest to the trawl fleet. In addition, the absence of cooperation between the two vessel groups leads to stock levels well below the safe minimum recommended by biologists (see Jakobsen, 1993).

In the next section of the paper the bioeconomic model is described. Following this is a section presenting the North-East Atlantic Cod fishery, and the data from this fishery that is applied in the model simulations. The results of the simulations are then presented, followed by a discussion. Finally some concluding remarks are made.

THE MODEL

We present a deterministic bioeconomic model, with two agents harvesting upon separate, but interacting sections of a fish stock. Henceforth, these two parts of the single stock will be called sub-stocks, and will interact via cannibalism and recruitment. The agent interaction is modelled in a dynamic game-theoretic setting, allowing us to study both cooperative and non-cooperative behaviour.

We concentrate on a single-stock version of the two-stock model presented by Lotka (1925) and Volterra (1928). Eide (1993) shows that this structure has a close fit to the biological findings regarding the changes in the North-East Atlantic Cod stock throughout the eighties. We describe the changes in the biomass levels of the two sub-stocks by the following difference equation:

$$\Delta x_{i,t} = G_i(x_{1,t-1}, x_{2,t-1}) - h_{i,t}, \quad i = 1,2 \qquad (1)$$

where $\Delta x_{i,t} = x_{i,t} - x_{i,t-1}$, and $x_{i,t}$ is the biomass of sub-stock i at time t, with $i=1,2$ defining immature and mature sub-stocks, respectively. It should be noted that $x_{i,t}$ can be expressed in terms of weight and number of fish to get $x_{i,t} = w_i * n_{i,t}$, where w_i is the average weight of sub-stock i and $n_{i,t}$ denotes the number of sub-stock i cod in period t. The rate of harvest of sub-stock i, is defined as $h_{i,t} = q_i x_{i,t} e_{i,t}$, where q_i is the catchability coefficient of vessel group i, and $e_{i,t}$ is the number of vessels deployed by i in period t.

The natural growth functions G_i, of sub-stock 1 and 2, also define the interaction between the two sub-stocks, and may be described as follows (Eide, 1993):

$$G_1(x_{1,t}, x_{2,t}) = r_1 x_{1,t}(1 - \frac{x_{1,t}}{a_1 x_{2,t}}) - b x_{1,t} x_{2,t}$$

$$G_2(x_{1,t}, x_{2,t}) = r_2 x_{2,t}(1 - \frac{x_{2,t}}{a_2 x_{1,t}}) . \qquad (2)$$

The parameters r_i, a_i and b are positive constants, with r_i being the intrinsic growth rate of sub-stock i. The parameter b determines the cannibalistic interaction, where the size of sub-stock 1 is negatively affected by that of sub-stock 2. By putting x_j into the growth function G_i $(i \neq j)$, as described in the bracketed terms in equation (2), we allow for a recruitment relationship between immature and mature fish.

It is assumed that two different agents or vessel groups, that is, trawlers and coastal vessels, designated 1 and 2, respectively, harvest upon each their respective sub-stocks, 1 and 2. Hence vessel group i only harvests sub-stock i[1]. Following Sumaila (1997), we let the cost function of a given vessel type i in period t, $C(e_{i,t})$, be defined as:

$$C\left(e_{i,t}\right) = \frac{k_i e_{i,t}^{1+\omega}}{1+\omega} \qquad (3)$$

where $\omega = 0.01$, and $k_i/(1+\omega) \approx k_i$ is the cost of engaging one fishing fleet (or vessel) for one year. Hence, the single period profit of vessel group $i=1,2$ can be expressed as:

[1] This is a simplification as there is overlap of harvesting, i.e. the coastal vessels harvest some immature cod, and the trawlers harvest some mature cod. Nonetheless, the two vessel groups do in fact target different sections of the cod stock. Armstrong (1997) shows that in 1993 almost 60% of the trawl harvest consisted of individuals less than seven years of age. More than 70% of the coastal vessel harvest consisted of individuals seven years and older.

$$\pi_{i,t} = \pi_i(x_{i,t}, e_{i,t}) = v_i h_{i,t}(x_{i,t}, e_{i,t}) - C(e_{i,t}) \qquad (4)$$

where v_i is the price per unit weight of sub-stock i. The stream of discounted single period profits of a vessel group, M_i, $i=1,2$, is defined as:

$$M_i(x_i, e_i) = \sum_{t=1}^{T} \delta_i^t \pi_i\left(x_{i,t}, e_{i,t}\right) \qquad (5)$$

Where $\delta_i = (1+r_i)^{-1}$ is the discount factor, and r_i denotes the interest rate of player i. Note that $t=1..T$ represents fishing periods, with T denoting the end period.

Under a cooperative regime, the goal of the cooperative agents is to find a sequence of effort, $e_{i,t}$ and sub-stock levels, $x_{i,t}$, $i=1,2$, to maximise a weighted average of their respective objective functionals (that is, their stream of discounted single period profits):

$$\Pi(x_1, x_2, e_1, e_2) = \beta M_1(x_1, e_1) + (1-\beta) M_2(x_1, e_2) \qquad (6)$$

subject to the stock dynamics given by equation (2) above, and the obvious non-negativity constraints. β and (1-β) indicate how much weight is given to the own objective functionals of 1 and 2, respectively, in the cooperative management problem. The following modified Lagrangian function can be set up for this problem (see Sumaila, 1995):

$$L(x_1, e_1, x_2, e_2; y) = \Pi(x_1, x_2, e_1, e_2) + y\phi^-(x_1, x_2, e_1, e_2) \qquad (7)$$

where y is a modified Lagrangian in the sense of Flåm (1993);

$$y\phi^-(x_1, x_2, e_1, e_2) := \sum_{t=1}^{T} \left[y_{1,t} \mathrm{H}(G_1(x_{1,t-1}, x_{2,t-1}) - h_{1,t} - \Delta x_{1,t}) + y_{2,t} \mathrm{H}(G_2(x_{1,t-1}, x_{2,t-1}) - h_{2,t} - \Delta x_{2,t}) \right]$$

and

$$\mathrm{H}(G_i(x_{i,t-1},x_{j,t-1})-h_{i,t}-\Delta x_{i,t}):=\begin{cases}1 & \text{if } \ (G_i(x_{i,t-1},x_{j,t-1})-h_{i,t}-\Delta x_{i,t})<0\\[2ex] 0 & \text{otherwise}\end{cases}$$

Under a non-cooperative regime, the problem of player i is to find a sequence of effort, $e_{i,t}$ and own sub-stock $x_{i,t}$ ($t = 1,2,\ldots,T$) to maximise his own objective functional denoted by M_i, subject to the relevant constraints. For this problem, the following modified Lagrangian function for each player can be formulated as:

$$L_i\left(x_i,e_i;x_j,e_j,y\right)=M_i(x_i,e_i)+\sum_{t=1}^{T}\left[y_{i,t}H(G_i(x_i,x_j,e_i,e_j)-h_{i,t}-\Delta x_{i,t})\right]\forall\ i\neq j \tag{8}$$

The key difference between the cooperative and non-cooperative scenarios is that in the latter each player maximises without regard for the intra-stock interaction between the two sub-stocks.

The solutions to equations (7) and (8) are pursued numerically using the solution procedure developed in Flåm (1993). From these solutions, we can determine the stock-sizes under cooperative and non-cooperative interaction between the two vessel groups. Furthermore, the optimal equilibrium harvest of the two sub-stocks can also be determined. Summing these for each t we obtain the total optimal equilibrium harvest in each time t.

THE NORTH-EAST ATLANTIC COD FISHERY

The North-East Atlantic Cod stock is a highly migratory fish stock, travelling through Norwegian and Russian exclusive economic zones, as well as international waters. Therefore Norway and Russia together annually determine the total allowable catch (TAC), giving each country approximately 45% each, with the remainder being harvested by third countries. The Russian and third country catch is mainly harvested by trawlers, while the Norwegian share of the TAC (the NTAC) is divided between two vessel groups; trawlers and coastal vessels. Since 1990 this division has been determined by a rule called the Trawl Ladder[2]. Upon the recommendation of Norwegian Fisher's Association, which organises both vessel owners and fishers, the Norwegian government chose to implement this allocation rule, which determines shares to the two vessel groups depending on the size of the NTAC. This rule stipulates that a minimum trawler share of 28% should be allocated when the NTAC is below 130,000 tonnes. For higher NTACs the trawler share increases, with a maximum trawler share of 33%, when the NTAC reaches 330,000 tonnes. Since almost all the non-Norwegian harvest is taken using trawl gear, this means that the total trawler share is approximately 70%, when the TAC for the North-East Atlantic Cod stock is large. This can then be compared to the optimal shares derived from our model.

The parameter values used in the simulations are based on data from Norwegian fishing vessels. The effort e_i, $i=1,2$, denotes the number of vessels within each vessel group.

[2] In actual fact, two different allocations rules have been implemented sequentially.

Hence, the economic parameters k_i, q_i and v_i are given the values in Table 1. Foreign trawlers are assumed to face the same economic and biological constraints as the Norwegian trawlers.

The discount rate δ is set equal to 0.07, as prescribed by the Norwegian Ministry of Finance, while b is found by Eide (1993) to be 0.2023.

SIMULATION RESULTS

Results pertaining to (i) discounted economic rents, (ii) harvest/harvest proportions, and (iii) standing stock sizes are given in Tables 2, 3 and 4, respectively.

Discounted economic rent

From Table 2, the following points can be made: First, we observe that the best total economic result (over 25 years) is NOK 30.71 billion obtained when β (which denotes the preferences of the trawler fleet) is equal to 0.6. Of this NOK 13.35 and 17.36 billion are obtained from the trawl and coastal fleets, respectively. Second, under non-cooperation, the potential economic benefits are wasted almost completely, with the coastal fleet and trawlers making respectively, NOK 1.47 and 1.37 billion. Third, as β approaches 0 or 1, total rent declines, an indication that allowing only the trawl or coastal fleet to exploit cod does not produce superior outcomes. The latter two results are in contrast to the results produced by Sumaila (1997); possible reasons for these differences are given in the discussion section of the paper.

Harvest/harvest proportions

The results here reinforce the points made under economic rent above. We observe in Table 3 that the optimal annual harvest computed, is 450,000 tonnes (when β=0.6), with the trawlers landing on average 198,000 tonnes, and the coastal fleet 252,000 tonnes. The best economic result is achieved when about 44% of the harvest is taken by the trawl fleet.

Table 3 also shows that non-cooperative behaviour leads to disastrous outcomes as all the harvest potential is virtually wiped out: the annual average harvest is only 78,100 tonnes.

In Figure 1 we observe that the optimal path of harvest for both vessel groups is increasing in the beginning of the 25-year period studied. After some time, however, the coastal harvest surpasses the trawler harvest, about the same time as the trawler harvest starts to decrease. Towards the end of the time period both vessel groups obtain decreasing harvests due to both discounting and decreasing stock levels. We see that in the non-cooperative case both vessel groups obtain decreasing harvests, and for all except the 1-2 first years, the non-cooperative harvests are well below the optimal.

Stock sizes

In Table 4, we observe that the stock size that supports the best economic solution occurs when β=0.6 at 2.99 million tonnes, with the stock sizes for the juvenile and adult stocks at 1.86 and 1.13 million tonnes, respectively. The table also reveals that non-cooperative behaviour is disastrous to the health of the stock. Indeed, threat of depletion is quite real here, as stock size is reduced to the dangerous level of about 0.26 million tonnes, a level that is well below the recommended 0.5 million tonnes minimum spawning biomass for a sustainable cod fishery (Jakobsen, 1993).

We observe in Figure 2 that the optimal stock paths of both sub-stocks are increasing in most of the time period studied. Towards the end of the 25 years, however, sub-stock 1 starts to decline, and is smaller than sub-stock 2 in the last year. This dip in sub-stock 2 is a result of discounting the future. In the case of a lower discount rate, this decrease does not appear. In the non-cooperative case, the sub-stocks decline drastically, the mature sub-stock being the smallest. At its smallest, sub-stock 2 is just over 6000 tonnes.

Sensitivity analysis

Table 5 shows that, as expected, with an increase in the cost of harvesting, the total profit to the two groups declines from NOK 30.71 to 29.60 billion, but the profits to the coastal fleet increases slightly, which means that the overall decline is accounted for by a decrease in trawler profits. Increase in costs also results in increase in stock size and a decrease in the trawler fleet share from 44% to almost 42%. These results are presumably due to the larger absolute harvesting costs of the trawler vessels. In addition, the reduction in trawler harvest which necessarily follows higher costs, leaves more prey for the mature sub-stock, allowing the coastal vessels to increase their harvests while trawler harvest share decreases.

Increase in prices have opposite effects to those we observe for increase in costs: A 25% increase in price leads to an increase in overall profits from NOK 30.71 to 35.11 billion. In this case, most of the gain in profits accrue to the trawler fleet. The effects on coastal vessel profits are however very small, both in the case of price and cost increases. In the case of price increase, the standing stock size decreases while the harvest share to the trawler fleet increases, for the same reasons stated in the above paragraph but acting in reverse direction.

A reduction of the discount rate from 7% to 5% results in an all-round increase in profits, leading to a total increase in economic rent of about 28% from NOK 30.71 to 39.27 billion. Two somewhat surprising observations can be made from the table. First, the stated decrease in the discount rate leads to about 5% increase in the trawlers' harvest share. Second, as the agents become less impatient with this change, one would have expected the stock to be allowed to grow larger. However, we see from Table 5 that this does not appear to be the case.

A possible reason for the above observations is that we study average sub-stock sizes over 25 years. In the case of a decreased discount rate the agents are less impatient regarding the increase in the sub-stocks, as viewed in Figure 2. Hence the sub-stocks increase in size more slowly, but the juvenile sub-stock is, nonetheless, by the end of the 25 year period larger than when the discount rate is higher. This also explains the increased share to the trawler fleet, which targets juveniles.

For an increase in the intrinsic growth rates, profits, harvests and stock sizes all increase, as one would expect. It is, however, of interest to note that the trawler harvest share is significantly reduced. One reason for this large decrease in trawl harvest share is the fact that since r_1 (juvenile intrinsic growth rate) is less than r_2, the growth in the mature sub-stock due to such changes is relatively greater than that of the immature sub-stock, hence reducing the optimal harvest share of the latter.

Finally, Table 5 reveals that an increase in the catchability coefficients by 25% leads to a decrease in the rent derived from the trawlers; and an increase in the rent from the coastal fleet. The total economic rent increases by over 15%. Similar trends are observed with respect to harvest, with the consequence that a significant reduction in the trawler harvest share from 44% to just over 38% is required. When it comes to stock levels, we see from the table that the juvenile stock size is lower at 1.76 compared to 1.86 million tonnes in the base case. On the other hand, the mature sub-stock level is higher at 1.25 compared with 1.13 million tonnes in the base case.

To explain the above results, one should note that the catchability coefficient is a measure of the efficiency of the fishing gear. Thus, what these results tell us is that an increase in the efficiency of the coastal fleet by up to 25% will be a very welcomed thing, but a similar increase in the case of the trawler fleet will be detrimental to both the economics and biology of the fishery, which is what one would expect given the present degrees of efficiency of the two groups of vessels.

DISCUSSION

A close look at Table 2 shows that the economic rents derived from the coastal fleet does not increase all the way as β approaches 0, as one would have expected. This is presumably because the low immature stock that emerges for low β values, as a consequence of the nature of the intra-stock interaction in the model, will not give sufficient positive effects upon the profits accruing to the coastal group. A larger immature stock (that comes as a result of a larger β) is more to the coastal group's advantage because of the recruitment coefficient a_2. However, this is the case only up to a certain point, where high β values increase the harvesting pressure from the trawlers, and also reduces the size of the mature sub-stock 2.

As stated earlier, the maximum total profit of NOK 30.71 billion is achieved when β=0.6. This outcome occurs when the trawler share of the total harvest is 44%. Hence, it is optimal that the coastal vessels obtain a greater share of the harvest, in order to reduce the predatory pressure on juvenile cod. The actual trawler harvest share of approximately 70% is well above the optimal share computed herein[3]. With the actual foreign harvest of 55% all being taken by trawlers, our results show that not only would it be advantageous for all the Norwegian quota to be taken by the coastal fleet,

[3] We must, however, keep in mind that in actual fact the trawler and coastal vessels harvest to some degree upon both sub-stocks. The effect of this upon the results is unclear, and is left for future research.

but some of the foreign harvest should be taken with coastal gear. This puts Norway's somewhat half-hearted efforts to encourage a Russian coastal fishery in a new perspective.

The actual harvest share allocated to the trawlers entails a much lower stock than the optimum. In our model a 70% share to the trawlers would result in an average stock size somewhere between 2.3 and 2.6 million tonnes, while the bioeconomically optimal average stock size is 2.99 million tonnes. Similarly the actual trawler harvest share would in equilibrium require a total harvest of between 270,000 and 320,000 tonnes, which is well below the optimal size of 450,000 tonnes given by our model. Likewise the profits would be only approximately 60% of the best total profits. All these clearly demonstrate that the current allocation is sub-optimal.

An important point to note is that the trawlers not only compete with the coastal vessels, but also with the mature sub-stock. Hence, the trawlers obtain the smaller profit when there is no cooperation. Also we see that, as is expected, the profits, harvests and stock sizes are much reduced in the non-cooperative case, compared to the cooperative situation. The trawler harvest share is however markedly below the actual harvest share. This is interesting from the cooperative viewpoint, as the non-cooperative solution is often deemed to be the agents' threat point in a bargaining situation. Even though there is no actual bargaining between trawlers and coastal vessels on the international arena, it is of interest to note what pressure a Norwegian coastal fleet could exert on the cod stock. It should be noted, however, that the trawler share in the non-cooperative case is above the share that is allotted them in the optimal cooperative case, the difference being 2.2%. This can be seen as an argument for the trawlers to obtain a larger share than that which our cooperative solution gives, hence partly explaining their large share in practice.

The bioeconomic optimal total harvest is, according to our model, 450,000 tonnes. This is well below the around 800,000 tonnes that has been harvested in recent years. It should be noted, however, that our result also includes low harvest levels in the years of the build-up of the stock, and at the terminal periods of the model. Hence, explaining the divergence to the very large harvests in recent years. The average harvest in the ten-year period 1984-93 is 357,000 tonnes (Anon, 1990, Anon, 1996). In the last few years the harvests have risen to about 800,000 tonnes. However, the latest signals from the biologists is that the TAC in coming years should be somewhat reduced[4].

Comparing our results with those of Sumaila (1997), we find that his non-cannibalistic model gives higher harvests and thereby also higher discounted profits than our model. This is due to the fact that, everything being equal, cannibalism reduces the stock along with the harvests, but also presumably due to differences in initial stock sizes used in the two models. Sumaila (op. cit.) obtains a corner solution requiring that the coastal vessels in the bioeconomic optimal situation be sole owners. In the current study, corner solutions are not obtained. The difference between the results from the two studies lies mainly in the different age structure and selectivity

[4] See *Fiskeribladet*, 28. October, 1997.

patterns assumed in the two models. The results obtained in the current analysis also gives far more devastating non-cooperative outcomes due to the same reasons.

We observe that the optimal profits and harvest shares are especially sensitive to changes in the intrinsic growth rates. This underlines the importance of the biological parameters in the model. The trawler harvest share is seen to be inversely related to the stock size from the sensitivity analysis on the intrinsic growth rates, with the implication that anything that increases the total average stock size, decreases the trawl harvest share. Apparently, this is because of increased predatory pressure upon the immature sub-stock that results from such increase.

CONCLUDING REMARKS

According to the findings of this study, in a bioeconomially optimal world, the trawlers should obtain 44% of the harvest of cod, a proportion that is much lower than the actual share of approximately 70% allocated to them.

Applying a Beverton and Holt model, Sumaila (1997) obtains a trawler share of approximately 60%. Sumaila's result is determined by the Nash bargaining solution, where the threat points play a central part. This model does not include cannibalism, and thereby gives a trawler threat point substantially above the coastal vessel threat point. We show that in the case of cannibalism this relationship is reversed, presumably explaining some of the difference between Sumaila (op. cit.) and our results. Armstrong (1997) obtains a trawler steady state harvest share of 52.4%, using a model that includes cannibalism. This is above our overall average trawler share of 44%. However, in our model we include the build-up phase of the stock: It may be the case that the coastal vessels obtain a higher harvest when average catches are considered than when steady state equilibrium harvests are, hence bringing down the overall average trawler share.

Central fisheries biologists in Norway have been sceptical to the use of harvesting as a regulatory mechanism for cannibalistic species[5], claiming that cannibalism is a part of the natural regulatory process of the stock. However, there is little scepticism from the same quarters when it comes to multispecies management, where the interaction between different species is apparently not seen as natural regulation. This seems to be a contradictory stance, whereby interactions *within* a single species harvested by heterogeneous harvesters is not seen in a similar light as interactions *between* species.

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[5] See *Fiskeribladet*, 16. July, 1997.

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Table 1. Economic and biological parameter values (q, the catchability coefficient, is a per vessel value; k, the cost parameter, is measured in 10^6 NOK per year; while v, the price, is in NOK/tonne; x_0, the initial stock size, is in thousand tonnes). Vessel group 1 consist of trawlers, while 2 describes the coastal vessels. Sub-stock 1 is immature cod, while 2 is mature cod.

Sub-stock/vessel group *i*

	1	**2**
r^1	0.5003	0.6728
a^1	8.7608	1.1880
q^2	0.006650	0.001175
k^3	18.602103	1.452341
v^3	7579	8655
x_0	783900	280500

[1] r, the intrinsic growth rate, and a, the growth parameter, are determined in Eide (1993).
[2] The catchability coefficients q_i are average values decided by the actual harvests, the vessel numbers (Anon., 1990, 1991, 1992, 1993), and the resulting stock sizes in the years 1990-93.
[3] The cost parameters are given by the weighted (with regard to number of vessels and year) cost data in Anon. (1990, 1991, 1992, 1993). The price parameters are the average prices that the two vessels obtained in 1992 (data from the Directorate of Fisheries).

Table 2. Profits in billion NOK (present value over 25 years), for 1<β<0, and for the non-cooperative outcomes. Numbers in bold indicate the profits that ensure maximum economic rent. Recall that β refers to the preferences of the trawl fleet.

	Profit		
β	**Trawl**	**Coastal**	**Total**
0.1	2,39	9.40	11,79
0.2	4.19	9.29	13.48
0.3	7.93	11.80	19.73
0.4	11.27	14.95	26.22
0.5	12.89	16.94	29.83
0.6	***13.35***	***17.36***	***30.71***
0.7	13.14	15.27	28.41
0.8	14.18	7.85	22.03
0.9	14.22	3.05	17.27
Non-cooperative			
	1.37	1.47	2.84

Table 3. Average harvest in million tonnes (over 25 years), for 1<β<0, and for the non-cooperative outcomes. Numbers in bold indicate the harvest/harvest share that ensure maximum economic rent.

	Average harvest			
β	**Trawl**	**Coastal**	**Total**	**trawl %**
0.1	0.0337	0.1550	0.1887	17.9
0.2	0.0667	0.1710	0.2377	28.1
0.3	0.1200	0.2100	0.3300	36.4
0.4	0.1670	0.2520	0.4190	39.9
0.5	0.1910	0.2660	0.4570	41.8
0.6	***0.1980***	***0.2520***	***0.4500***	***44.0***
0.7	0.1980	0.2080	0.4060	48.8
0.8	0.2270	0.1010	0.3280	69.2
0.9	0.2380	0.0386	0.2766	86.0
Non cooperative				
	0.0361	0.0420	0.0781	46.2

Table 4. Average stock size in million tonnes (over 25 years), for 1<β<0, and for the non-cooperative outcomes. Numbers in bold indicate the harvest/harvest share that ensure maximum economic rent.

	Average stock size		
β	**stock1**	**stock2**	**Total**
0.1	1.470	0.354	1.824
0.2	1.620	0.446	2.066
0.3	1.980	0.615	2.595
0.4	2.140	0.834	2.974
0.5	2.050	1.010	3.060
0.6	***1.860***	***1.130***	***2.990***
0.7	1.680	1.190	2.870
0.8	1.760	0.901	2.661
0.9	1,660	0.707	2.367
Non cooperative			
	0.1780	0.0839	0.2619

Table 5. Sensitivity analysis: Profits, harvest and stock sizes giving maximum economic rent, for an increase in the costs k_1 and k_2, the prices v_1 and v_2, and the intrinsic growth rates r_1 and r_2, and catchability q_1 and q_2, by 25%, and a reduction in the discount rate, δ, from 0.07 to 0.05. The base case in bold defines the optimal results with β=0.6. Profits are in billion NOK, while the harvest and stock sizes are in million tonnes.

	Profit			Average harvest				Average stock size		
	Trawl	Coastal	Total	Trawl	Coastal	Total	Trawl %	stock1	stock2	Total
Base case	**13.35**	**17.36**	**30.71**	**0.198**	**0.252**	**0.450**	**44.0**	**1.860**	**1.130**	**2.990**
k ↑ 25%	12.13	17.47	29.60	0.190	0.263	0.453	41.9	1.940	1.200	3.140
v ↑ 25%	17.73	17.38	35.11	0.217	0.211	0.428	50.7	1.600	0.795	2.395
r ↑ 25%	20.13	30.16	50.29	0.276	0.441	0.717	38.5	2.590	1.460	4.050
q ↑ 25%	12.91	22.52	35.43	0.188	0.304	0.492	38.2	1.760	1.250	3.010
δ = 0.05	18.43	20.84	39.27	0.242	0.250	0.492	49.1	1.740	0.858	2.598

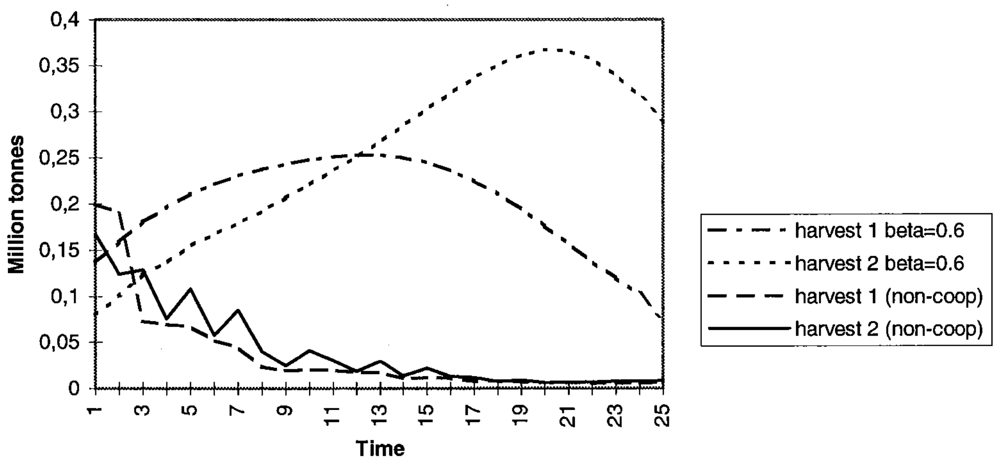

Figure 1. Harvest profiles over a 25 year time period for the optimal cooperative and non-cooperative cases. Note that harvest 1 and 2 refer to trawl and coastal fleet harvests, respectively.

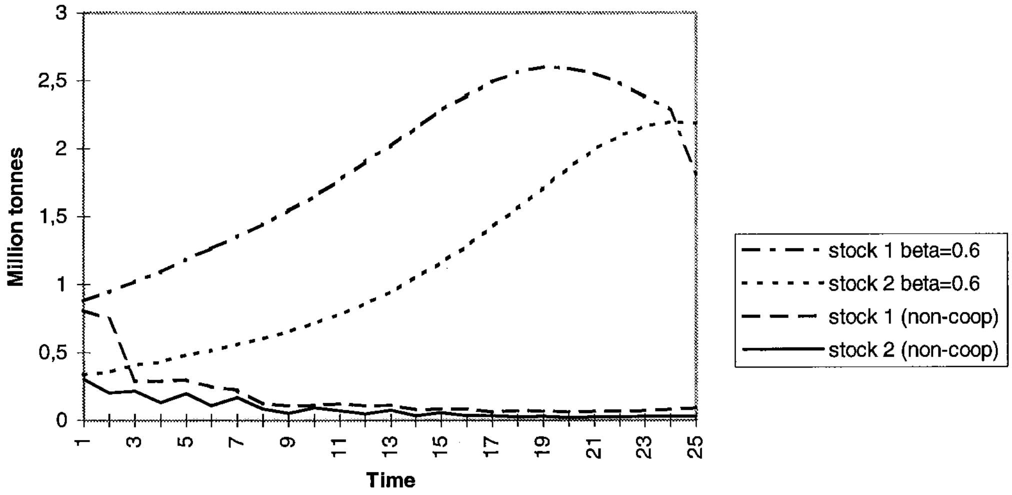

Figure 2. Sub-stock profiles over a 25 year time period for the optimal cooperative and non-cooperative cases. Note that stock 1 and 2 refer to trawl and coastal fleet stock sizes, respectively.

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