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**Scope for Efficient Multinational Exploitation
of North-East Atlantic Mackerel**

by

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Introduction

Since the introduction of powerful harvesting technologies and the growth in demand for fish as a food source, unregulated fish stocks are prone to over exploitation and collapse. Game-theory has provided reasons for anticipating this outcome if a fish stock remains as a common property resource.

A minimal level of regulation to prevent stock collapse is to impose total allowable catches (TACs) that are likely to ensure that stock biomass remains high enough to prevent collapse. Bioeconomic models have been used to estimate the TACs necessary to maximise the present value of future rents from a fish stock. These TACs are typically much more stringent, and hence more unpalatable to operators in the industry in the short term. Perhaps because of this, to date no regulator has adopted rent maximisation for setting TACs. Alternatively, it may be that the goals of government are more weighted towards maintenance of fishing activity in the short-run, or towards community and employment considerations, than on economic efficiency.

It was expected that the introduction of the Law of the Sea and the recognition of nations' rights to declare exclusive economic zones (EEZs) would allow governments to set TACs to maximise rents if they so desired, because they would be able to control access to the EEZs. As discussed by Bjørndal (2001), Munro (2001), and Bjørndal and Munro (forthcoming), it was subsequently realised that this did not necessarily provide the conditions for rent

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maximisation if a fish stock in one EEZ also straddled the EEZ of another nation, or of international waters.

The scope for strategic interaction between nations has led to further game-theoretic analysis of the conditions suitable for rent maximisation, and applications of the analysis to many different fisheries. The practical relevance of this wider multinational analysis still depends on the extent to which rent maximisation is seen as a goal of government, and if it is, most importantly, the plausibility of the predicted gains and losses accruing to the nations involved from alternative cooperative arrangements.

The aim of this paper is to investigate the scope for multinational cooperation in setting national TACs for EEZs and a TAC for international waters so as to maximise rents for the North-East Atlantic mackerel fishery. The stock is harvested by some coastal nations that have mackerel in their EEZs at different times of the year, and by others that can otherwise harvest mackerel in international waters. Comparisons are made between current harvesting and stock levels, and levels under cooperative rent maximisation, and non-cooperative rent maximisation.

Similar work on multinational gaming has been conducted for Norwegian spring-spawning herring, another pelagic stock that shares some of the same feeding grounds, and is harvested by an overlapping group of nations (Lindroos 2000; Arnason et al. 2001; and Lindroos and Kaitala 2001). The extension of the analysis to multinational exploitation of multispecies stocks is an obvious future but more complex project.

The North-East Atlantic mackerel stock

North-East Atlantic mackerel consists of three separate stocks, referred to as the North Sea, Western and Southern components, based on different spawning grounds (ICES 2000). For management purposes they are treated as one stock, because the stocks mix at times when they are jointly harvested. The Western component is by far the largest, accounting for 71 to 86 per cent of the stock (ICES 2001). The North Sea stock is currently heavily depleted.

North-East Atlantic mackerel is a straddling stock, subject to harvesting at different times of the year by the countries whose fishing zones they pass through. The major coastal-state

harvesters of North-East Atlantic mackerel are Norway, Scotland and Ireland. In quarter 1 shoals migrate from the Northern North Sea to the area off the North West coast of Scotland, when the stock is heavily fished by Scotland and Ireland. After spawning in quarter 2, primarily off the West coast of Scotland and in the Irish Sea, much of the catch in quarter 3 is taken by Russia and Norway in the Norwegian and Northern North Seas. Russia's catch is mainly in the international waters, variously referred to as the Ocean Loop, the Banana Loop, and the Herring Loophole. In quarter 4 Norway continues to take a significant catch in the Northern North Sea.

ICES makes recommendations on annual TACs for North-East Atlantic mackerel by fishing area, on criteria of biological sustainability. The coastal players conduct negotiations to agree the distribution of the TACs that are set after taking account of the ICES recommendations. The distributions tend to be based on recent catch levels, a policy that sometimes leads to inefficient catch behaviour and mis-reporting. The North-East Atlantic Fisheries Commission (NEAFC) plays the role of a regional fisheries management organization in obtaining agreement between the coastal and non-coastal players on the distribution of the quota set for the catch in international waters. For example, NEAFC has arranged agreement on allocation of the international waters' quota of 65,000 tonnes for 2001 between the Russian federation (38,000 t), Denmark (on behalf of the Faroes and Greenland), the EU and Norway (22,000 t), Iceland (2,500 t), and Poland (1,000 t).

Catch history over the last ten years is shown in Figure 1. Catches have fluctuated, averaging about 400 thousand tonnes per year, with the EU and Norway taking similar amounts.
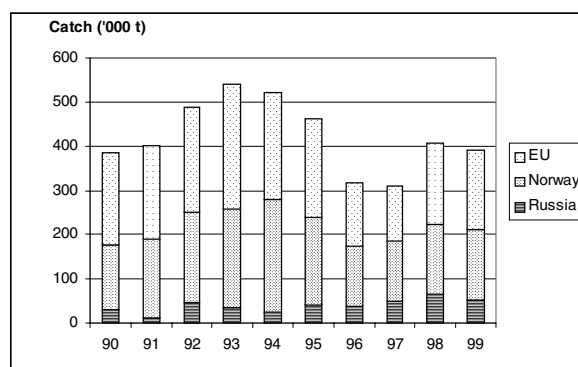

Figure 1: Catches by Russia, Norway and the EU, 1990-1999

Source: ICES (2001b)

A model is formulated in the next section that characterises the harvesting of North-East Atlantic mackerel as determined by the three major harvesters with alternative cooperative behaviour, outside the actual institutional arrangements for management. The aim is to identify the maximum rents to harvesters under alternative cooperative and non-cooperative coalition arrangements from harvests over the first 20 years of a 30-year planning horizon. Harvesting profiles and present values for alternative coalition arrangements over time can be compared with current levels, and some deductions made on harvester goals and incentives for cooperative arrangements.

The Model

The formulation and structure of the model is developed in this section. A flow chart summarising seasonal cohort flow, fishing mortality, and harvesting, is presented in Appendix Figure A1.

Players

The major harvesters of North-East Atlantic mackerel, Russia and Norway, and the EU members, Scotland and Ireland (designated EU henceforth) are indexed by j = 1 to 3 respectively.

Fishing seasons and areas

The model is run for a finite time horizon of Y years, starting with year 1 as the base year, 2000. Track is kept of harvesting, spawning and marketing by season of the year $(s = 1,...,4)$, corresponding to calendar quarters $(q = 3,4,1,2)$. All harvesting occurs in seasons 1 to 3. Spawning takes place in season 4 (quarter 2). Although in reality harvesting does occur in season 4, it is relatively low at about 10 per cent of annual harvest, and is ignored in the modelling. In recent years about 30 per cent of the total catch has been taken in each of the seasons 1 to 3 (ICES 2000, pp. 32-33). Marketing in each year is completed by the end of season 3.

Russia and Norway, and Scotland and Ireland in the EU, took 73 per cent of the total catch in 1999, with percentages distributed between them of 12, 39 and 49 respectively (ICES 2000).

They took 70 per cent of the total catch[2] in 1999 from ICES Divisions IIA (Norwegian Sea), IVA (Northern North Sea) and VIA (North-west Coast of Scotland and North Ireland), the areas which accounted for 82 per of the total catch. Approximating the current pattern of fishing by major harvester, season and area, the modelled pattern is as shown in Table 1.

Table 1: Areas fished by harvester and season

Harvester		Season		
		$s=1$	$s=2$	$s=3$
Russia	$j=1$	IIA Norwegian Sea (International Waters)		
Norway	$j=2$	IVA Northern North Sea	IVA Northern North Sea	
EU	$j=3$			VIA North-west Coast of Scotland and North Ireland

Based on ICES (2000), Table 2.2.2.6, *Catches of mackerel by Division and Sub-area in 1999*, p. 56.

Age cohorts

Following the biological modelling of mackerel by ICES (2000), there are 13 year classes of mackerel $(a = 0,...,12)$, with the four age-12 classes for each season including fish aged 12 and above. Fish numbers are tracked across seasons s within each year y, in line with constant natural mortality m, and seasonal across-cohort fishing mortality set by the j-th harvester, $f_{j,y,s}$. The number fish in millions in cohort a in year y in season s is denoted $x_{a,y,s}$.

Stock Dynamics

The stock recruitment relationship is that used in ICES (2000, p. 46) for medium term predictions. Season-1 recruits at age 0 into the fishery in year y in millions, $x_{0,y,1}$, is an Occam-type function of spawning stock biomass in year y-1, SSB_{y-1}. Below the threshold of 2,348 thousand tonnes, recruits are a positive linear function of SSB_{y-1}, and above the threshold recruitment is constant at 4,252 million, so that:

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[2] Other countries included England, Wales and Northern Ireland, Denmark, the Netherlands, Germany and the Faroe Islands.

$$
x_{0,y,1} = \begin{cases} 1.811\, SSB_{y-1} & \text{if } SSB_{y-1} \leq 2,348 \text{ thousand tonnes} \\[2em] 4,252 & \text{otherwise} \end{cases} \tag{1}
$$

where $SSB_{y-1} = 2,348$ thousand tonnes is the threshold stock, equal to the minimum estimated SSB in the Western mackerel SSB time series (1972 - 96) scaled by the ratio of the mean of the North-East Atlantic SSB to the that of the Western component (1984 - 96); and $x_{0,y,1} = 4,252$ million fish is the geometric mean (1972-1996) of recruitment to the Western mackerel, raised by the ratio (1.156) of the estimated Western and North-East Atlantic mackerel recruitments for the period 1984-1996 (ICES 2000, pp. 45-46).

Spawning stock biomass in year y is the sum of the season-4 biomass ws_a in each age cohort a weighted by maturity u_a:

$$
SSB_y = \sum_{a=0}^{12} x_{a,y,4} ws_a u_a \tag{2}
$$

Entry numbers into the age-0 cohort in subsequent seasons, and into older cohorts in all seasons, depend on aggregate fishing mortality $g_{a,y,s}$ at an annual rate across all players j for cohort a in season s of year y:

$$
g_{a,y,s} = \sum_{j=1}^{3} q_{j,a,s} f_{j,y,s} \tag{3}
$$

where $q_{j,a,s}$ are age-specific selectivity coefficients which translate the across-cohort fishing mortality $f_{j,y,s}$ into cohort specific fishing mortality. Natural annual mortality m, constant across all age classes, is added to obtain total mortality, giving the updating equation as:

$$
x_{a',y',s'} = x_{a,y,s} \exp(-(g_{a,y,s} + m)\Delta t) \quad \forall \ (a',s') \neq (0,1) \text{ and } (12,1) \tag{4}
$$

The LHS indices a', y', s' are the corresponding RHS indices updated by one season, according to:

$$
a', y', s' = \begin{cases} a, y, s+1 & \text{if } s = 1, 2 \text{ or } 3 \\[1.5em] a+1, y+1, 1 & \text{otherwise, for } a < 12, \ y < Y \end{cases} \tag{5}
$$

Δt is the seasonal time step equal to 0.25 years. Equation (4) is used for determining $x_{a',y',s'}$ for all (a',s') from $(0,2)$ to $(12,4)$, except for $(a',s') = (12,1)$ where Equation (6) applies. This allows for fish aged 12 or older still surviving at the end of season 4 to be included in next season-1's age-12 cohort for accounting purposes, in addition to the standard flow of fish aged 11 at the end of season 4.

$$x_{12,y+1,1} = x_{11,y,4}\exp(-(g_{11,y,4}+m)\Delta t) + x_{12,y,4}\exp(-(g_{12,y,4}+m)\Delta t) \tag{6}$$

As an approximation it is assumed that all parameters specific to age-12 mackerel, such as weight and selectivity coefficients, also apply to older mackerel. The second component of the RHS of (6) is shown in Figure A1 by the broken link arrow between box $x_{12,y,4}$ and box $x_{12,y+1,1}$.

Harvests

Assuming fishing mortality is applied at a constant rate throughout each season, the total of instantaneous harvests ('000 tonnes) for the j-th player is:

$$
\begin{aligned}
h_{j,y,s} &= f_{j,y,s}(\sum_{a=0}^{12} wc_{j,a,s}x_{a,y,s}q_{j,a,s}\int_{0}^{\Delta t}\exp(-(g_{a,y,s}+m)\tau)d\tau) \\
&= f_{j,y,s}(\sum_{a=0}^{12} wc_{j,a,s}x_{a,y,s}q_{j,a,s}(1-\exp(-(g_{a,y,s}+m)\Delta t))/(g_{a,y,s}+m)
\end{aligned}
\tag{7}
$$

where $wc_{j,a,s}$ is the average weight of mackerel (kg) caught by harvester j at age a in season s.

Net revenue

Player j's net revenue from harvesting in year y is defined as:

$$NR_{j,y} = TR_{j,y} - TC_{j,y} \qquad \forall\, j, y \tag{8}$$

where $TR_{j,y}$ is total revenue and $TC_{j,y}$ is total cost. Net revenue is received at the end of season 3, and so the present value of the stream of net revenues across the planning horizon is:

$$PVNR_j = \sum_{y=1}^{Y} NR_{j,y}(1+r)^{-(y-0.25)} \qquad (9)$$

where r is the annual rate of discount.

Total Revenue from harvesting

The price of mackerel has been relatively buoyant over the last five years, due mainly to strong demand from Japan, driven by reductions in the Japanese catch of chub mackerel. Most mackerel is now sold for human consumption. Norway has emerged as the major supplier to the Japanese market. Other major markets for mackerel are Eastern Europe, Russia, and Nigeria (see Asche and Aarland 2000; Asche, Bjørndal, and Hole 1998; Hannesson 2000; Hempel 2000; and Nakamoto 2000).

Factors affecting the price each harvester receives are the total harvest of all harvesters, the season of the catch, the average weight of the fish, and demand in the final markets. These factors are considered in this section and quantified for modelling the revenue generated for each of the three harvesters in the model. All mackerel prices are given in Norwegian Kroner, adjusted to 1999 base-year prices using the Norwegian CPI (Statistics Norway 2000). Mackerel prices given in US and UK currency have been converted using exchange rates published by the Bank of England (2001).

FAO data on traded prices of frozen mackerel over the 1990's are shown in panel (a) for mackerel imports and in panel (b) for mackerel exports in Figure 2. The major importing countries are Japan, Nigeria and Russia. Except for 1994, the Japanese import price has been significantly higher than the prices for Nigeria and Russia (panel a). In 1998 economic problems in Russia and East European nations led to reductions in their purchasing power and a fall in prices (Hempel 2000).

Higher Japanese prices can be explained by Japanese consumers demanding higher quality mackerel in characteristics such as size and oil content. Temporary shortages may also be a factor. Japanese demand for imported mackerel has grown as a result of reduced domestic catches following over harvesting.
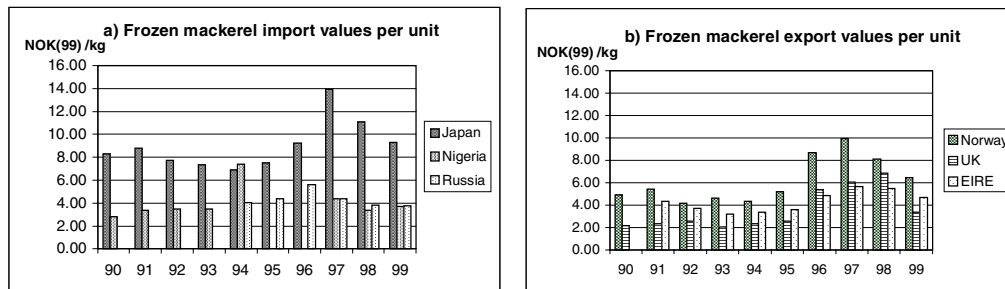

Figure 2: Import and export prices of frozen mackerel, 1990-1999

Source: FAO (2001)

Panel (b) of Figure 2 shows export prices of mackerel obtained by Norway, the UK and Ireland over the 1990's. Norway's prices consistently exceeded those of the UK and Ireland, and were much higher in 1996 and 1997. Hempel (2000) refers to EU mackerel exports losing market share in Japan, Russia and Asia, while gaining in Africa in 1998. It needs to be pointed out though that the FAO data must allow for a large component of Norwegian exports being re-exports because recorded exports exceed production. Hannesson (2000) points out that in 1989 and 1999 imports were 80 per cent of the Norwegian catch.

Norwegian export and import prices by country, and by weight category (above or below 600 g), are given in Figure 3, for years since 1992 for which data have been published. Panels (a) and (b) show Norway received higher prices from Japan than from Russia and Poland within each weight category, and higher prices for the heavier fish, particularly from Japan in 1996. Norway's exports to Japan accounted for about 50 per cent by weight of Norwegian exports of mackerel less than 600g, and about 70 per cent of mackerel in the heavier category, over the period 1992 to 2000.
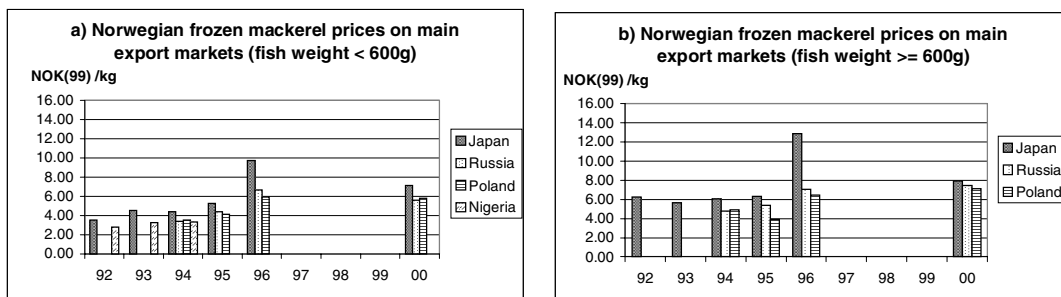
Figure 3: Norwegian export prices by importing country and weight category, 1992-2000

(Statistics Norway 1993 to 1997 and 2001. Data are not available for those years for which no values are shown.)

There is evidence of strong seasonality in UK mackerel prices (DEFRA 2001, pp. 71-72, 178-179). The average seasonal price for 1999 and 2000 was highest in season 1, and lowest in season 3. Oil content and weight, which are positively correlated with price, peak in season 2 (quarter 4), prior to migration to spawning areas. The average season-3 price was 81 per cent of the season-4 price. Given the seasonal progression of fishing from Russia and Norway in season 1, to Norway in season 2, and to the EU in season 3, this ordering of countries is also the ordering of reduced prices received. It supports the historical relative export prices received by Norway and the EU shown in Figure 4.
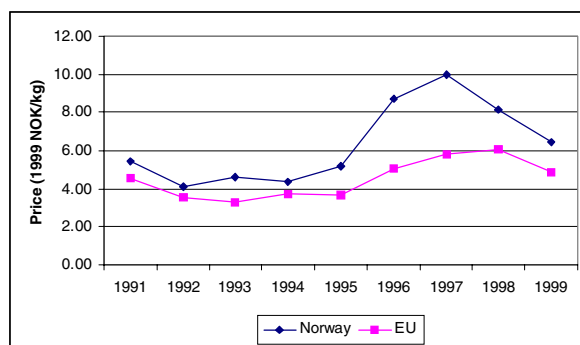
Figure 4: Mackerel prices received by Norway and the EU, 1991-1999

Source: FAO (2001)

In the modelling, the relativity of prices between the three harvesters is fixed. For the three years 1997 to 1999, the average export price received by Norway was 1.19 relative to the weighted average export price for Norway and the EU combined of 1.00 (FAO, 2001). This compares with 0.81 for the EU. The factors $\psi_2 = 1.19$ and $\psi_3 = 0.81$ are used for multiplying the modelled mean price of mackerel, a function of total harvest, to determine Norwegian and

EU prices. In the absence of volume and value trade statistics for Russia, a value of $\psi_1 = 1.00$ is taken for determining the Russian price. Russia, as primarily an importer of mackerel, is not selling on high-price markets, but its market value is likely to be high given that it is predominantly harvesting in a high-price season.

Over the nineties there was a strong negative correlation between price and harvest. A good fit was obtained for a linear regression of Norway and EU weighted export price on production of Russia, Norway and the EU over the years 1991 to 1999. The results are presented in Table 2, and show significant intercept and slope coefficients.

Table 2: Parameter estimates for inverse linear demand schedule for mackerel

Symbol	Regression coefficient	t statistic	Adjusted R^2
α (intercept)	13.8542	8.61	
β (slope)	-0.0190	-5.12	0.76

Sources: ICES (2001), FAO (2001), Statistics Norway (2001b), Bank of England (2001)

The equation was used as the mackerel inverse demand schedule in the model as follows:

$$P_y = \alpha + \beta H_y \tag{10}$$

where P_y is the weighted export price of export mackerel from Norway and EU in NOK 1999 per kg, and H_y is the total catch in thousand tonnes:

$$
\begin{aligned}
H_y &= h_{1,y,1} + h_{2,y,1} + h_{2,y,2} + h_{3,y,3} \\
&= H_{1y} + H_{2y} + H_{3y}
\end{aligned}
\tag{11}
$$

which is the sum of Russia's harvest in season 1, Norway's in seasons 1 and 2, and the EU's in season 3.

Total revenue for the j-th harvester in year y is

$$TR_{j,y} = \psi_j H_{j,y} (\alpha + \beta H_y) \tag{12}$$

Total cost of harvesting

The total cost of each player j's effort in catching $h_{j,y,s}$ in season s given in Eq (7) is:

$$TC_{j,y,s} = c_{j,s} e_{j,y,s} \tag{13}$$

where $c_{j,s}$ is cost per unit effort. It is assumed that the modified Schaefer harvest function

$$h_{j,y,s} = w_{y,s}^{\gamma} e_{j,y,s}^{\phi} \tag{14}$$

applies, where the units of effort follow from the units of harvest and stock biomass, and where $w_{y,s}$ is the biomass of the aggregate stock, defined as:

$$w_{y,s} = \sum_{a=0}^{12} x_{a,y,s} w s_a \tag{15}$$

with ws_a the weight at age in the stock in the base year.

Harvest function (14) allows for harvest to be directly proportional to both harvesting effort and stock biomass for both exponents equal to one. The stock exponent $\gamma = 1$ is reasonable if the stock is uniformly distributed in the sea. However, if a stock, such as mackerel, schools and can be subjected to directed fishing, a fall in stock biomass is likely to lead to a less than proportionate fall in harvest, implying $\gamma < 1$.

An effort exponent $\phi < 1$ arises if additional harvesting requires greater than proportionate additional days at sea, or if there is asymmetry in the cost of harvesting for changes in effort due to the irreversibility of capital investment in vessels. For example, an increase in effort may incur a cost for increases in vessel capacity, as well as direct costs. An equivalent reduction in effort may not save the same vessel capacity cost if the opportunity cost of use of vessels is zero.

From Eq (14) effort $e_{j,y,s}$ as a function of harvest $h_{j,y,s}$ is

$$e_{j,y,s} = (h_{j,y,s} w_{y,s}^{-\gamma})^{1/\phi} \tag{16}$$

which makes j's total cost of catch effort in each season s :

$$TC_{j,y,s} = c_{j,s} (h_{j,y,s} w_{y,s}^{-\gamma})^{1/\phi} \tag{17}$$

and j's total cost for year y: $\qquad TC_{j,y} = \sum_{s=1}^{3} TC_{j,y,s} \tag{18}$

The value of the cost coefficient for the j-th harvester is set at the level which ensures that for base-year harvest $\bar{h}_j$ and base-year price $\psi_j \bar{p}$ in 1999, total cost is the estimated base-year proportion of total revenue, $\theta_{j,s}$, or:

$$c_{j,s} = \theta_{j,s} \psi_j \bar{p} \bar{h}_{j,s}^{(1-1/\phi)} \bar{w}^{\gamma/\phi} \tag{19}$$

where $\bar{w}$ is the estimated base-year stock biomass.

In the model, values of θ for Norway are taken to be 0.83, based on operating expenses as a proportion of operating revenues for all vessel sizes fishing pelagic species in 1998 and 1999 (Directorate of Fisheries 2001, Tables H4 and H5). For lack of similar data available for the other harvesting nations, the same values were adopted for these nations also. This is likely to be a reasonable assumption for UK and Irish vessels that use similar types of vessel and gear, but there is less certainty about the applicability of the assumption for Russia.

The stock and effort exponents in the Schaefer harvest function (14) have not been estimated empirically and are therefore varied to test the sensitivity of results to their values. In model runs the stock exponent γ is set at 1.0, 0.6 and 0.0 to cover a range of possibilities from uniform distribution of mackerel to shoaling of mackerel. To indicate the degree of convexity in total cost as a function of harvest level introduced by reducing the effort exponent below 1, total cost is plotted in Figure 5 for values of ϕ equal to 1.0, 0.8 and 0.6, for the case of Russia. All three schedules pass through the same point for the base year harvest $\bar{h}_1 = 51,000$ tonnes. In model runs ϕ is set at 0.8 and 0.6 to cover a range of convexity from slight to strong.
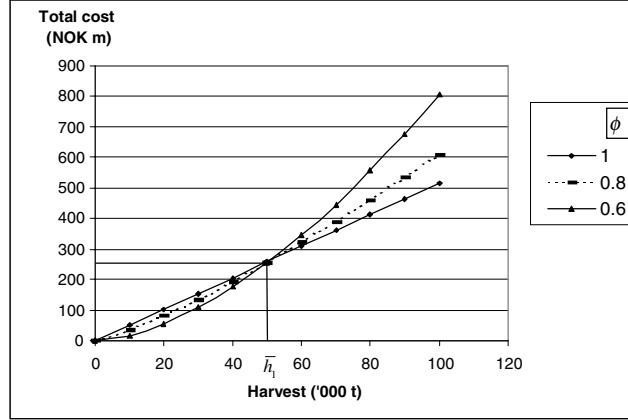
Figure 5: Total harvest cost for alternative effort exponents, centred on Russia's 1999 harvest, $\overline{h}_1$

Modelling alternative coalition behaviour

The behaviour of the grand coalition is modelled as a straightforward maximisation problem. In the case of other coalition arrangements, the strategic interaction of two or more players results in non-cooperative dynamic Nash equilibria.

Cooperative joint maximisation of net revenues

Russia, Norway and the EU set fishing mortalities for each year of the planning horizon of Y years so as to maximise the present value of combined net revenue over the planning horizon. The problem is:

$$\max \sum_{j=1}^{3} PVNR_j = \sum_{j=1}^{3} \sum_{y=1}^{Y} NR_{j,y} (1+r)^{-(y-0.25)} \tag{20}$$
$$\text{with respect to} \quad f_{j,y,s} \geq 0 \qquad \forall \quad j, y, s$$

The outcome must be Pareto optimal because by maximising joint benefits it is impossible for any player to increase their benefit by changing their fishing plan without loss to another player. It is the outcome achieved by the grand coalition of players. However, in practice for various reasons harvesting nations do not combine to obtain the efficient outcome. Whilst the harvesting countries may view total returns as measurable in currency, and hence transferable, they may not be wholly financial flows, as for example if consumer surplus were recognised as a return. This may make sharing of the total benefit more difficult. Another

problem that inhibits joint maximisation is lack of knowledge of the counterfactual. The grand coalition is formed presumably with each country supposing they will achieve a share of joint returns that will make them better off than if they go it alone, but if they join, how do they know what they would have gained otherwise?

Non-cooperative maximisation of coalition net revenues

In the case of three players, there are three possible coalition subgroups of two members (denoted RN_E, NE_R and RE_N, where R, N, E stand for Russia, Norway and EU, and the break point separates the coalition groups). There remains the possibility that all players are non-aligned (denoted R_N_E), representing three coalitions of one member. This makes four possible coalition groupings outside the grand coalition.

It may be rational for a coalition to form if the coalition can take actions to maximise returns for its members, subject to all other coalitions similarly taking actions to maximise returns for their members. For each coalition grouping, denoting each coalition in turn by n, and the remaining coalitions by $\bar{n}$, the coalition n faces the problem:

Find $f^*_{n,y,s} \geq 0$ which maximises

$$PVNR_n = \sum_{y=1}^{Y} NR_{n,y}(1+r)^{-(y-0.25)} \qquad \forall \quad n \tag{21}$$

$$\text{subject to} \quad f_{\bar{n},y,s} = f^*_{\bar{n},y,s} \qquad \forall \quad \bar{n}, y, s$$

A setting of $f_{j,y,s} \; \forall \; j, y, s$ that satisfies (21) is a dynamic non-cooperative Nash equilibrium.

The Nash equilibrium solutions were obtained using the following convergent process based on (21) :

> For successive iterations k, starting with $k=1$, find $f^k_{n,y,s}$ which maximises $PVNR_n$ subject to $f^k_{\bar{n},y,s} = f^{k-1}_{\bar{n},y,s}$. (For those low k for which $f^{k-1}_{\bar{n},y,s}$ does not exist, $f^{k-1}_{\bar{n},y,s}$ is set equal to zero.) Iterations continue until the difference between $f^k_{n,y,s}$ and $f^{k-1}_{n,y,s}$ for all n is negligible, at which point $f^k_{n,y,s}$ is taken to equal $f^*_{n,y,s}$ and iterations cease.

Nash solutions were obtained within 30 iterations.

Results

Results for all country alignments are given initially for the base parameter settings detailed in Appendix Tables A1 and A2, with the stock exponent $\gamma = 1$ and effort exponent $\phi = 0.8$. The planning horizon Y is set at 30, though all net present values and harvest profiles are given for the first 20 years of the planning horizon. This is to avoid any significant divergence of results for years approaching the planning horizon from those for an infinite planning horizon, due to the incentive to draw down stock with zero terminal value. In practice, the draw-down effect on the approach to year 30 is very minor for the model parameter settings (see Appendix A3). All net present values (NPVs) are present values of net returns over years 1 to 20, in millions of NOK for the base year 1999.

The NPV of returns for all five coalitions are given in Table 3, and displayed in Figure 6. NPVs under joint maximisation (RNE) are much greater for Norway (15,893) than those for Russia (2,234) and the EU (692). Norway's NPV reduces substantially under all four coalition groupings, though still remains the highest of the three. Norway's NPV is lowest under the single-member coalitions, the non-cooperative outcome, at 6,574. The EU's NPV under non-cooperation compared to under joint maximisation is relatively high at 3,972. For Russia it is 3,148.

Table 3: Harvester NPVs of returns for all coalitions

Country alignment	Net present value of returns			
	Russia	Norway	EU	Total
RNE	2,234	15,893	692	18,819
RN_E	1,631	8,303	5,521	15,455
NE_R	5,471	9,669	1,244	16,384
RE_N	3,307	8,957	3,801	16,065
R_N_E	3,148	6,574	3,972	13,694
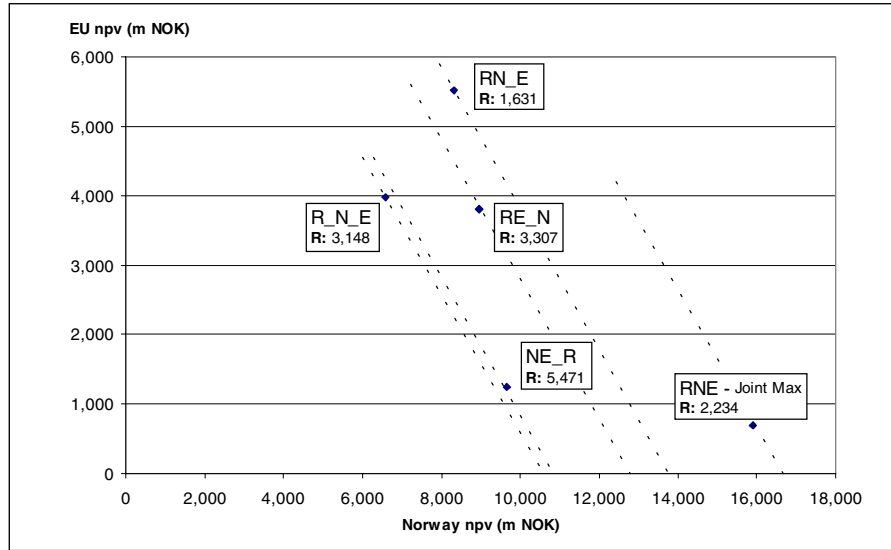
Figure 6: Coalition returns in Norway NPV and EU NPV space

The difference in harvest profile under non-cooperation compared to joint maximisation can be seen by comparing panels (a) and (b) in Figure 7. Under joint maximisation total harvest rises from 182 tonnes in year 1 to 243 tonnes in year 20. Corresponding total harvests under non-cooperation rise from 293 to 362 tonnes. The actual total tonnage in 1999 was just under 400 tonnes (see Figure 1). This underscores a common result. Even under non-cooperation, planned harvests are less than under loose regulation because each harvester is rent maximising, albeit in a suboptimal context. Consequently even under non-cooperation, there is little danger of non-sustainable fishing. The modelled SSB rises from 4.00 million tonnes to 5.60 million tonnes in year 20 (to 6.49 million tonnes under joint maximisation).

a) Joint maximisation (RNE)   b) Non-cooperation (R_N_E)

Figure 7: 20-year harvest solution profiles for base-run parameters

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The proportion of total harvest contributed by each harvester is quite different. Under joint maximisation, Norway is the predominant contributor. The EU contribution in year 1 is very small at about 11 per cent, compared to the actual 1999 contribution of 46 pe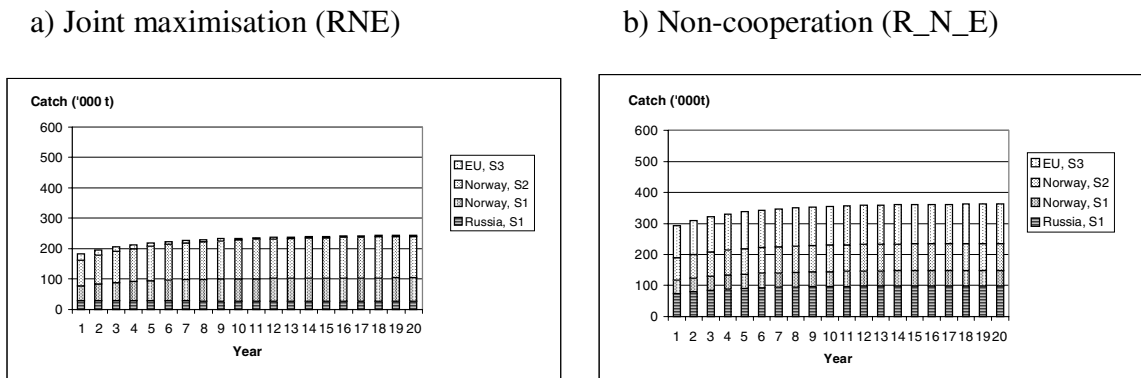r cent, and declines markedly. Under non-cooperation the contribution starts at 36 per cent and remains fairly stable. Thus it appears that non-cooperation mimics current harvesting behaviour more closely than does joint maximisation (compare modelled catches in panels a and b with recent catches in Figure 1).

Turning to incentives for the formation of coalitions, the 3-dimensional harvester NPVs of Table 3 are represented in Figure 6 in Norway NPV and EU NPV space, with one-for-one NOK trade-off lines through each coalition outcome. The NPV for Russia is given at each coalition outcome point. It is clear that without transfers or side-payments, no coalition (including the grand coalition) dominates any other. Regarding total NPVs for coalition combinations, between the joint maximisation in the grand coalition (RNE – 18,819) and the non cooperative outcome (R_N_E – 13,694), the three two-member coalitions are bunched around a NPV of about 9,000 for Norway and a total NPV of about 16,000, with inversely related NPV's for Russia and the EU. For all three of these coalitions, the other single-member always gains higher NPVs than when they are in coalition.

The only coalition grouping which cannot be blocked, or is in the core, is the non-cooperative three single-member grouping. The EU's NPV in the non-cooperative grouping is their second highest out of all of the coalition groupings. Norway's is the lowest.

If monetary transfers are possible, transfers can be engineered under the grand coalition which make it the only member of the core, or which cannot be blocked by any other coalition. It transpires that one such transfer arrangement is that which gives each harvester their Shapley value. The Shapley value for each harvester is the weighted sum of the contributions the harvester makes to each possible coalition (Dixit and Skeath 1999). The contribution a harvester makes to a coalition is the total payoff to the coalition less the total payoff to the coalition excluding the harvester. Contributions are shown in Table 4 based on the harvester NPVs for each coalition shown in Table 3.

Table 4: Harvester contributions and Shapley values

Coalition	NPV of Contribution		
	Russia	Norway	EU
RNE	7,906	11,711	8,885
RN	3,360	6,786	
NE		6,941	4,340
RE	3,136		3,960
R	3,148		
N		6,574	
E			3,972
Shapley values	4,767	8,383	5,669

For example, Russia's contribution of 7,906 to the grand coalition is calculated as the joint return of 18,819, less the payoff of (9,669 + 1,244 = 10,913) to the Norway and the EU in the NE_R grouping. Russia's contribution of 3,360 to the RN coalition is calculated as the joint return of (1,631 + 8,303 = 9,934), less the payoff of 6,574 to the Norway on its own. Russia's contribution to the R coalition, compared to not being a participant, is its non-cooperative payoff of 3,148.

In the three-harvester case, the weights on a harvester's contributions to each of the coalitions they could belong to are 1/3 for the grand coalition, 1/6 for each of the two two-member coalition groupings, and 1/3 for the non-cooperative grouping. These are based on each size of coalition to which the harvester could belong being equally likely, namely 1/3 for each of the coalition sizes of 3, 2 and 1.

The resulting Shapley value for each harvester is shown in the bottom line of Table 4, and again in Table 5 (run 1) together with the transfers required. Norway transfers 2,533 to Russia and 4,977 to the EU. Although this does not have to be the case, from the NPVs in Table 4 it can be checked that the Shapley values do belong to the core. Norway pays the larger sum to the other harvester with the greatest incentive to otherwise ensure a non-cooperative outcome.

Thus redistributing the total return from the most efficient outcome under the grand coalition so that each harvester receives their Shapley value is one redistribution that would forestall the otherwise most inefficient outcome of non-cooperation. Compared with other

redistributions that could also achieve this, the Shapley redistribution is seen as desirable in incorporating an incentive for efficiency (Shapley values are proportional to contributions), and fair in the sense that all sizes of alternative coalitions are weighted as equally likely. These are both characteristics that make adoption of Shapley transfers more likely. However, probably the most important factor determining their acceptance and adoption would be the credibility of the modelled NPV outcomes for the different coalitions. As some check on this, the sensitivity of the qualitative results to uncertain parameter values is considered.

Sensitivity analysis

Parameters which have not been empirically estimated for this study are the stock and effort exponents in the Schaeffer harvesting equation (14), γ and ϕ. Bjørndal (1989) estimated exponents of generalized Cobb-Douglas supply and production functions for North Sea herring, a pelagic stock with similar behaviour to mackerel. He estimated stock exponents of 0.62 and 0.34 with high standard errors for alternative model formulations, and 0.38 and 0.56 for the effort exponents. In more recent work Bjørndal and Gordon (2000) find that average harvesting costs of purse seiners catching Norwegian Spring-spawning herring to be fairly constant despite substantial changes in stock size. Analysis of the sensitivity of results to these exponents is therefore important. The Shapley values for alternative settings are shown in Table 5.

Table 5 shows that for all of the parameter sets tested, Norway makes transfers to Russia and the EU, with the transfer to the EU about double that to Russia. The incentives for coalition formation are the same for solutions in runs 2 to 6 as they are for run 1. If monetary transfers are not feasible, the non-cooperation solution is in the core, and no other. If monetary transfers are feasible, joint maximisation solutions with Shapley value transfers are in the core.

Table 5: Shapley values and required transfers for alternative parameter settings

Run	Parameter settings	Net present value of returns			
		Russia	Norway	EU	Total
1 (Base)	**gamma = 1.0, phi = 0.8, r = 0.05**				
	Shapley values	4,767	8,383	5,669	18,819
	Joint maximisation	2,234	15,893	692	18,819
	Required transfer	2,533	-7,510	4,977	
2	**gamma = 1.0, phi = 0.6, r = 0.05**				
	Shapley values	3,814	9,906	6,816	20,536
	Joint maximisation	3,079	13,298	4,158	20,536
	Required transfer	735	-3,393	2,658	
3	**gamma = 0.6, phi = 0.8, r = 0.05**				
	Shapley values	4,056	7,744	5,484	17,285
	Joint maximisation	2,211	13,693	1,380	17,285
	Required transfer	1,845	-5,949	4,104	
4	**gamma = 0.6, phi = 0.6, r = 0.05**				
	Shapley values	3,291	9,259	6,652	19,202
	Joint maximisation	2,760	11,596	4,846	19,202
	Required transfer	530	-2,336	1,806	
5	**gamma = 0.0, phi = 0.8, r = 0.05**				
	Shapley values	2,997	6,690	5,184	14,871
	Joint maximisation	1,894	10,268	2,709	14,871
	Required transfer	1,104	-3,579	2,475	
6	**gamma = 1.0, phi = 0.8, r = 0.10**				
	Shapley values	3,143	5,614	3,763	12,519
	Joint maximisation	1,556	10,366	597	12,519
	Required transfer	1,587	-4,752	3,165	

Reducing the effort exponent ϕ from 0.8 to 0.6 for $\gamma = 1.0$ (runs 1 and 2), and for $\gamma = 0.6$ (runs 3 and 4), markedly reduces the transfers required to achieve the Shapley values for each player. The transfer to Russia is reduced to roughly a third, and to the EU to roughly a half, of that for $\phi = 0.8$. The Shapley values change also, but by a much lower order of magnitude. The result can be explained by the reduction in ϕ lowering the inequality of returns to the players under joint maximisation. Harvests and returns increase for Russia, and even more substantially for the EU, at Norway's expense. The increased convexity of the total harvest cost schedule resulting from reducing ϕ from 0.8 to 0.6 has already been shown in Figure 5. The increased convexity reduces the extent to which Norway can exploit its price advantage on overseas markets.

The transfers required to achieve the Shapley values are also reduced as the stock exponent γ is reduced from 1.0 to 0.6 to 0.0 for $\phi = 0.8$ in runs 1, 3 and 5, but to a lower extent. The

effect of a reduction in γ on harvest profiles across years is to reduce the incentive to initially harvest at a low level to obtain a cost advantage from higher stocks later. For $\gamma = 0$, the year-1 harvest for the EU under joint maximisation is double the harvest for $\gamma = 1.0$. Harvests are virtually unchanged from year 1 to year 30. Year-30 stocks are higher, indicating that whilst it is optimal to harvest earlier at a higher level, over all years it is optimal to harvest less intensively.

Quotas on mackerel harvesting are higher than would be economically efficient. To the extent that the industry is able to influence quota setting, this may indicate that the industry is more likely to take a shorter-term view of benefits accruing from fishing. The real discount rate may be higher than market rates. In run 6 the stock and effort exponents are as for run 1, but the rate of discount is increased from 5 to 10 per cent per annum. The time profiles of harvests are only marginally increased, and there is no change in coalition incentives.

An important question is what planning horizon should be used in the analysis. As there is no non-arbitrary horizon, an infinite horizon is perhaps appropriate. All modelled NPVs have been given for the first 20 years of a 30-year planning horizon. Both the 20 and the 30-year time spans are arbitrary, but in appendix A3 it is shown that the NPVs for the first 20 years in the optimal solution to the problem with an infinite planning horizon would be very little different. Consequently, the coalition incentive systems would not change.

The main result is that for a wide range of parameter values, the grand coalition is unstable if there is no redistribution of the joint maximisation NPV profile. Without transfers the outcome is the type of non-cooperative fishing currently observed. However, there is scope for achieving the efficiency gains of joint maximisation by suitable transfer of the joint benefits, such as that given by the Shapley values.

Discussion and Conclusions

Perhaps not so surprisingly, joint maximisation policies show optimal harvest levels to be about half current levels, and significant growth in stocks. Kennedy (1992) found that the optimal long-run level of fishing effort directed at western mackerel in 1989 would be one half to one third of actual effort. However, under non-cooperation (single-member coalitions only), the Nash equilibrium harvests are still much lower than the TACs currently set. This reflects the prevailing practice of setting TACs as high as possible, whilst avoiding any likelihood of stock collapse under the precautionary principle.

Various issues arise. How important are the rents generated from mackerel stocks, to the industry and to government? Should the harvesting nations or nation groups negotiate between themselves to set the TAC in a rent generation framework rather than a biological sustainability framework? Alternatively, if some other goal besides rent maximisation has a higher ranking in the social objective function, such as maximisation of labour employed in the industry, there is no reason why gaming analysis should not be conducted with that goal.

Even if economic efficiency were seen as an important social goal, there would be no guarantee that this would be achieved under agreement between all harvesters to harvest through time so as to maximise joint producer rents. It may be that total social rent is regarded as including consumer surplus as well as producer surplus. If the catch is exported, lower prices benefit foreign and not domestic consumers, and normal practice in cost-benefit analysis is to accord such benefits zero weighting. However, in this application, one of the harvesting nations is a net importer, namely Russia, so there is an argument for including Russian consumer surplus in the objective functions of coalitions.

The current system of agreeing the allocation of the TAC is quite different from that modelled in the gaming scenarios. In current negotiations for allocation of both coastal state and international waters TACs, shares tend to be worked out on the basis of recent harvest activity, or claims of relative proportions of stock in EEZs. The system to some extent gives the impression of fairness, or at least the system does lead to agreed outcomes. However, as already mentioned, the system is not immune from strategic manipulation, with possibly undesirable social outcomes. Moving to a system of negotiating with specific goals such as rent maximisation might lead to more desirable social outcomes, but agreement may be more difficult to achieve. The modelling results for mackerel together with results from other

studies show that there is often scope for arranging transfers of joint rents to ensure players receive their Shapley values, within a stable grand coalition.

As already emphasised, the acceptability of Shapley values is likely to depend on the credibility of the estimates of player payoffs under the different possible coalition arrangements. Although the model results show the efficacy of Shapley values under a wide range of parameter values, harvesting nations are likely to accept the system more readily if all parameters are empirically estimated. To this end, the stock and effort exponents in the mackerel harvesting function should be estimated.

Three important simplifications in the model should be borne in mind in considering the results. One is the assumption of perfect knowledge in each player committing to future harvesting decisions. Each player's understanding of the biology of the fish stock, and of the decision-making processes of other players, is imperfect. This means that returns for competing coalitions are likely to be lower than those modelled.

Restricting the number of players to three is another simplification. This leads to the overestimation of returns compared to modelling more players if the excluded smaller players are less efficient than the main three. Also, harvesting by the three main players is likely to be greater in the short run in the knowledge that they face competition for access to stocks from other players.

A third caveat is the absence of any density dependence in the biological modelling. Even for non-cooperative harvesting solutions, modelled stock levels rise after 30 years to levels about 40 per cent higher than current stocks. No allowance is made for possible changes in age-dependent natural mortality or in recruitment at these stock levels.

An interesting extension of the modelling would be the introduction of Japan as a fourth player. Japan's decisions on the TAC setting on stocks of chub mackerel within their EEZ (Yatsu et al. 2001; and Hernandez and Ortega 2000), and restrictions on imports of North-East Atlantic mackerel, interact strategically with the harvesting decisions by European nations through marketing and price effects. Japan's objective function might be the present value of net revenue from harvesting mackerel, plus consumer surplus accruing to Japanese consumers of mackerel. There is also an interaction on the production side to the extent that Russia is a major harvester of chub mackerel in the Sea of Japan.

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Figure A1: Flow chart for modelling the harvesting of North East Atlantic mackerel
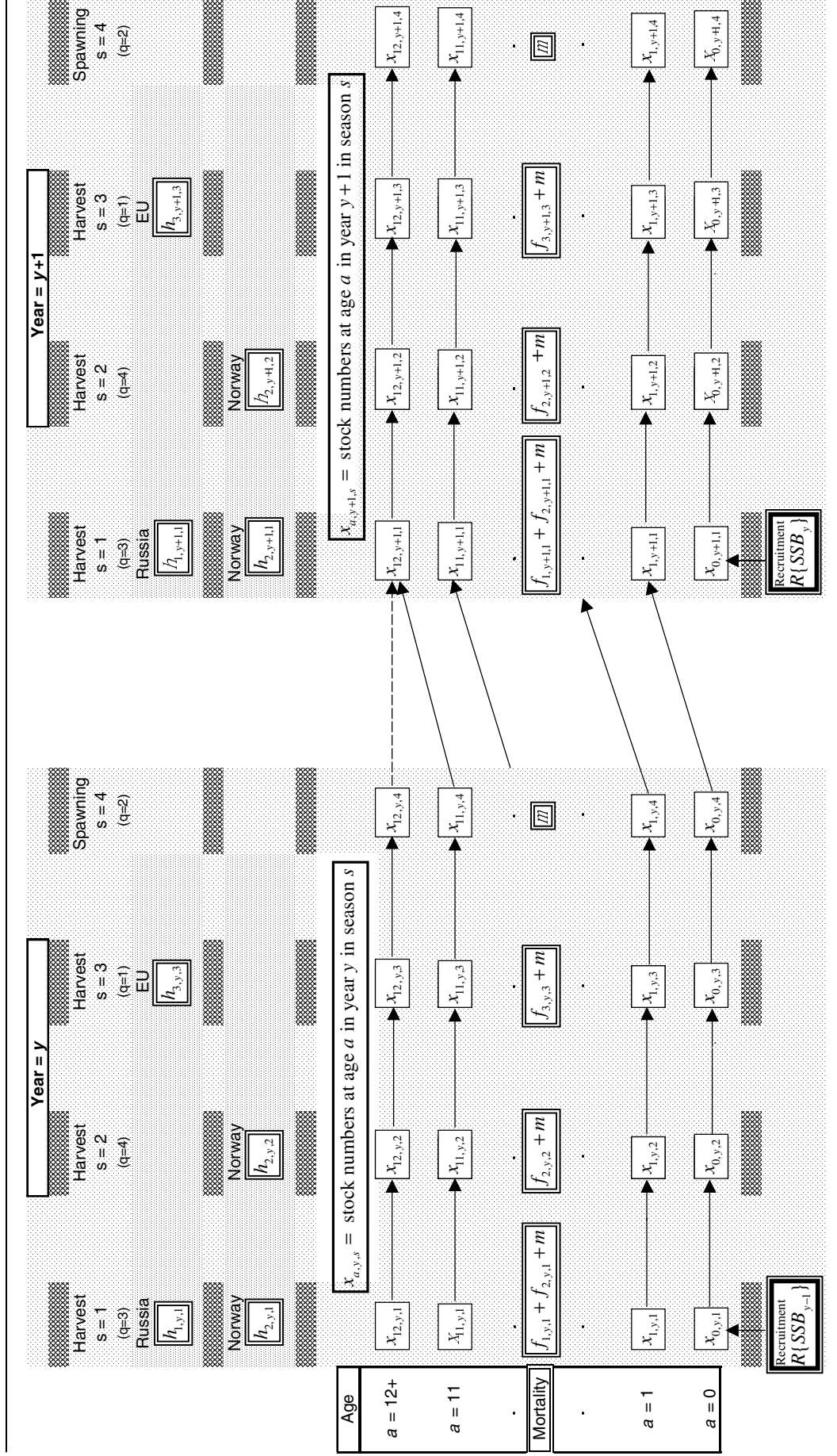
Appendix Table A1: Model Variables and Parameters

Indices

y	Year index ($y = 1,\ldots,Y$)
s	Season index ($s = 1,\ldots,4$)
a	Age index ($a = 0,\ldots,12$)
j	Harvester index (**1** for Russia; **2** for Norway; **3** for Scotland and Ireland (EU))

Decision variables

$f_{j,y,s}$	Across-cohort fishing mortality

Parameters[†]

α, β	Intercept and slope of linear inverse demand schedule	13.85, -0.0190
γ	Stock exponent in harvesting function	1.0 (0.6, 0.0)
ϕ	Effort exponent in harvesting function	0.8 (0.6)
$\theta_{j,s}$	Total cost as a proportion of total revenue in base year	0.83, 0.83, 0.83, 0.83
ψ_j	Harvester mackerel price factor	1.00, 1.19, 0.81
$\overline{h}_{j,s}$	Base-year harvest ('000 tonnes)	51, 50, 110, 180
m	Natural mortality rate	0.15
$\overline{p}$	Base-year mean marketed fish price (NOK /kg)	6.13
$q_{j,a,s}$	Harvesting selectivity coefficients	*Table A2, cols 5,7,9,11*
r	Rate of discount (p.a.)	0.05 (0.10)
$\overline{w}$	Base-year stock biomass ('000 tonnes)	5160
u_a	Proportion of fish sexually mature	*Table A2, col 3*
$wc_{j,a,s}$	Mean fish weight in catch (kg)	*Table A2, cols 6,8,10,12*
ws_a	Mean fish weight in the stock (kg)	*Table A2, col 4*
$x_{a,1,1}$	Initial stock numbers (million)	*Table A2, col 2*
Y	Number of years in planning horizon	30 (20, 60, 100)

[†]Values for the base run are given in column 3 or in Table A2 if they are age-specific. Figures in brackets are alternative values to those used in the base run.

Endogenous variables

		Equation
$c_{j,s}$	Cost (NOK) per unit of standardised effort	(19)
$e_{j,y,s}$	Harvesting effort	(16)
$g_{a,y,s}$	Cohort-specific fishing mortality	(3)
$h_{j,y,s}$	Player harvest ('000 tonnes)	(7)
$H_{j,y}, H_y$	Marketed harvest ('000 tonnes)	(11)
$NR_{j,y}$	Net revenue (million NOK)	(8)
P_y	Mean marketed fish price (NOK /kg)	(10)
$PVNR_j$	Present value of net revenue stream over Y years (million NOK)	(9)
$w_{y,s}$	Stock biomass ('000 tonnes)	(15)
SSB_y	Spawning stock biomass (million tonnes)	(2)
$TC_{j,y,s}, TC_{y,s}$	Total cost (million NOK)	(17), (18)
$TR_{j,y}$	Total revenue (million NOK)	(12)
$x_{0,y,s}$	Stock recruitment numbers for both $y, s \neq 1$ (million)	(1)
$x_{a,y,s}$	Stock numbers for $a > 0$ and both $y, s \neq 1$ (million)	(4), (6)

Appendix Table A2: Age specific parameters

Age	Initial stock numbers	Maturity ogive	Weight in the stock	Russia Season 1 Area IIa		Norway Season 1 Area IVa		Norway Season 2 Area IVa		EU Season 3 Area VIa	
a	$x_{a,1,1}$	u_a	ws_a	$q_{1,a,1}$	$wc_{1,a,1}$	$q_{2,a,1}$	$wc_{2,a,1}$	$q_{2,a,2}$	$wc_{2,a,2}$	$q_{3,a,3}$	$wc_{3,a,3}$
	(million)		(kg)		(kg)		(kg)		(kg)		(kg)
0	4252	0.00	0.000	0.0000		0.0000		0.0000		0.0000	
1	3645	0.09	0.091	0.0000		0.0000	0.178	0.0000	0.178	0.0000	0.123
2	3709	0.60	0.191	0.0587	0.291	0.0033	0.297	0.0061	0.299	0.0020	0.191
3	3095	0.87	0.243	0.1090	0.389	0.0247	0.360	0.0298	0.362	0.0256	0.252
4	3168	0.98	0.302	0.1360	0.403	0.0294	0.418	0.0470	0.408	0.0344	0.323
5	1989	0.98	0.359	0.1729	0.458	0.0593	0.460	0.0771	0.456	0.0755	0.358
6	1213	0.99	0.409	0.1090	0.530	0.1026	0.509	0.1358	0.488	0.1431	0.416
7	1155	1.00	0.441	0.0762	0.540	0.1074	0.553	0.0828	0.539	0.1166	0.463
8	575	1.00	0.473	0.0593	0.565	0.1128	0.596	0.1250	0.566	0.1179	0.482
9	292	1.00	0.510	0.0531	0.601	0.1287	0.602	0.1286	0.576	0.1536	0.538
10	153	1.00	0.538	0.0662	0.631	0.1723	0.632	0.1337	0.629	0.1602	0.538
11	126	1.00	0.517	0.0625	0.632	0.0969	0.664	0.1033	0.650	0.0808	0.561
12+	203	1.00	0.609	0.0970	0.754	0.1626	0.734	0.1308	0.715	0.0904	0.619

Data in columns 2 to 4 for $x_{a,1,1}, u_a$, and ws_a are those used in ICES (2000) medium-term modelling projections starting January 1, 2000, for the "Northern" mackerel stock made up of the western area including the North Sea and catches taken in international waters in ICES Division IIa.

Selectivity coefficients $q_{j,a,s}$ are catch in numbers at age for Western Atlantic mackerel in ICES (2000) Table 3.2.1.1, divided by initial stock numbers in column 2, and normalised to sum to one across a. Weights in catch $wc_{j,a,s}$ are for Western Atlantic mackerel in ICES (2000) Table 3.2.1.2.1. Data for Western mackerel rather than for North-East Atlantic mackerel as a whole are used for modelling the "Northern" stock because of the predominance of the western stock. ICES (2000) uses relative weights for calculating stock weights for North Sea, Western and Southern mackerel components of 0.02, 0.73 and 0.25 respectively.

Appendix A3: Approximating solutions for an infinite planning horizon in programming models

Mathematical programming models can be used for finding the sequence of decisions that maximises the net present value of returns over a finite planning horizon. If the planning horizon is really infinite, and computing resources are finite, what approximations can be introduced to the problem so that solutions approximate solutions to the infinite planning horizon problem?

Giving terminal values to assets still on hand at the end of the planning horizon is one method. However, the terminal values will generally be the net present value of the optimal income stream from the end of the planning horizon onwards.

In deterministic multicohort fisheries problems, it is often the case that there is an optimal steady state stock and annual harvest which once attained holds indefinitely. The value of the stock once the steady is reached is the present value of the annual steady state rent as a perpetuity. The steady state stock and annual harvest can be determined making use of the fact that the marginal value of a unit of the steady state stock does not change from one year to the next. However, it is more difficult to determine the optimal approach path to the steady state.

Conrad (1999), in a textbook example of using Solver in Microsoft Excel spreadsheets to determine optimal harvesting of a fish stock, where no account is taken of the different ages of fish in the stock, includes the following terminal value. It is the present value of rents that would be received in perpetuity from the end of the planning horizon. To ensure the rents are sustainable, the stock at the end of the year for which the perpetual rent is calculated is constrained to be at least as great as the stock at the beginning of the year.

The idea can be applied to a multicohort fishery problem, with a multicohort constraint for sustainability that stock numbers in each age category must be at least as great at the end of the year after the planning horizon as the beginning.

The joint maximisation objective function for a planning horizon of T years is:

$$\max = \sum_{t=1}^{T} NR_t (1+r)^{1-t} \tag{1}$$

To obtain solutions that approximate solutions obtained over an infinite planning horizon, objective functions such as (1) with a planning horizon of T years can be changed to:

$$\max \sum_{t=1}^{T-1} NR_t (1+r)^{1-t} + NR_T (1+r)^{-T+1} / r \tag{2}$$

$$\text{subject to} \quad x_{i,T+1} \geq x_{i,T} \quad \forall i \tag{3}$$

where $x_{i,t}$ is stock number in age group i at the beginning of year t.

Constraint (3) ensures that the net return from harvesting in year T, NR_T, could be sustained or bettered in all subsequent years in perpetuity. The second term in (2) is the present value of receiving NR_T in perpetuity, and is a lower limit of the value of year T stocks across all age categories. Adding the second term presents an incentive to increase year $T-1$ stocks so long as the present value of harvesting thereby foregone is more than offset by the present value of the perpetuity.

The value of (2) is less than the value obtained from pursuing an optimal harvesting strategy in perpetuity to the extent that (3) holds as an inequality. The greater T, the closer the solution for year T-1 is to the steady state solution, and the closer will be the two sides of inequality (3). T needs to be at least larger than the number of age groups to ensure that constraint (3) can be satisfied for any opening stock numbers by age group.

The solutions shown in Table A3 to the mackerel problem of maximising the NPV of joint rents using finite planning horizons of 20, 30, 60 and 100 years, and to the problems of maximising approximately the NPV of rents over an infinite planning horizon with the same number of decision stages, can be compared.

All the indications are that the solution to the *100 inf* problem is very close to the solution for the first 100 years of the infinite planning horizon problem. The across-cohort fishing mortality values $f_{1,y,1}, f_{2,y,1}, f_{2,y,2}, f_{3,y,3}$ (for Russia, season 1; Norway, season 1; Norway, season 2; and EU, season 3) deviate very little from 0.11, 0.34, 0.67 and 0.02 from years $y = 27$ to 100. Minor increases of up to 0.01 can occur from one year to the next for one harvester, offset by similar decreases for another harvester. Equation 3 holds as an equality, which means that the fishing mortalities are optimal steady state mortalities.

Table A3: Results for alternative planning horizons for joint maximisation of the NPV of RNE rents, for $\gamma = 1.0$, $\phi = 0.8$, and $r = 0.05$

	Planning horizon							
	20 fin	20 inf	30 fin	30 inf	60 fin	60 inf	100 fin	100 inf
SSB20	6.45	6.51	6.49	6.51	6.50	6.50	6.50	6.50
NPV20	18,825	18,806	18,819	18,813	18,817	18,817	18,817	18,817
SSB30			6.55	6.59	6.59	6.59	6.59	6.59
NPV30			23,770	23,763	23,765	23,765	23,765	23,765
SSB60					6.57	6.61	6.62	6.61
NPV60					29,845	29,844	29,844	29,844
SSB100							6.58	6.61
NPV100							31,415	31,415

'Y' fin is a model run with a finite planning horizon of 'Y' years
'Y' inf is a model run with a finite planning horizon of 'Y-1' years, with a terminal value on stock numbers
     equal to the present value of sustainable rents from year 'Y' onwards indefinitely
SSB'Y' is spawning stock biomass at the beginning of year 'Y' in million tonnes
NPV'Y' is net present value of joint rents at the end of year 'Y' in million NOK

The solution to the *100 fin* problem is similar for years 27 to 93. Stock drawdown occurs from year 94 to year 100, effected through increases in $f_{3,y,3}$. The optimal year-100 across-cohort fishing mortalities for the *100 fin* problem are 0.12, 0.32, 0.66, 0.19.

Two main conclusions follow from Table A3. Firstly, the results over the first 20 years of the solution to the 30-year planning horizon problem (as reported in the main body of the paper) can reasonably be taken to be the results for the first 20 years of an infinite planning horizon for this problem. The values of SSB20 and NPV20 for the *30 fin* problem are little different from those for the longer planning horizon problems, and in particular, from those for the *100 inf* problem.

Second, the *inf* problem with objective function (2) and constraint (3) gives fishing mortalities for the last stage which are very close to the optimal steady state fishing mortalities for this problem with 30 or more decision stages. As expected, the *fin* problems show stock drawdown effects, with lower SSB and higher NPV for the final decision stage. This suggests that the *inf* problem formulation is a simple and efficient means of obtaining a good approximation to the solution to the infinite planning horizon problem, using mathematical programming with a finite number of decision stages.