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S Pascoe, S Mardle, F Steen
and F Asche

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Centre for the Economics and Management of Aquatic Resources (CEMARE), Department of Economics, University of Portsmouth, Locksway Road, Portsmouth PO4 8JF, United Kingdom.

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Interactions between farmed salmon and the North Sea Demersal fisheries: a bioeconomic analysis

Sean Pascoe[1], Simon Mardle[1], Frode Steen[2] and Frank Asche[2]*

1). Centre for the Economics and Management of Aquatic Resources
University of Portsmouth
Locksway Road
Southsea PO4 8JF, UK

2). Department of Economics
Norwegian School of Economics and Business Administration
Helleveien 30
N-5035 Bergen-Sandviken, Norway

*corresponding author
CEMARE, University of Portsmouth, Locksway Road
Southsea PO4 8JF, UK
Phone: +44 23 9284 4242
Fax: +44 23 9284 4037
Email: sean.pascoe@port.ac.uk

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Interactions between farmed salmon and North Sea fisheries

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Abstract

The growth in farmed salmon production since the early 1980s, and the subsequent decline in salmon prices, has caused considerable concern about the implications for the price of wild caught species. Changes in prices affect the incomes of fishers, as well as the level and distribution of effort in a fishery. This in turn affects the stock size of the different species within the fishery, with consequences for future production.

In this paper, a dynamic bioeconomic model of the North Sea Demersal fishery is linked to a salmon supply model through a price formation model. The model is used to estimate the potential effects of market interactions between the species on the production of both farmed and wild caught species and profitability of the fishery. The results suggest that the effects of market interactions between farmed and wild caught species are less predictable than indicated in earlier studies.

Key words: bioeconomic model, market interactions, aquaculture, salmon, North Sea

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Introduction

The farmed salmon industry in Northern Europe (particularly Norway and Scotland) and South America has grown considerable since the early 1980s. This has been accompanied by a corresponding growth in salmon consumption world wide. In France, per capita consumption of salmon has increased threefold between 1982 and 1995 (Le Grel, Corre and Tuncel 1998). Total consumption of salmon in Spain increased by a factor of thirteen between 1980 and 1996 (Robinson and Pascoe 1998). This large increase in consumption has largely been the result of falling salmon prices, which has made salmon more accessible to a wider consumer group. Salmon prices in the EU fell by 50 per cent between 1994 and 1996 (Asche and Steen 1998).

Per capita consumption of all fish products has generally increased in the EU over the last decade in response to a range of factors (e.g. health benefits of fish and perceived health risks associated with other meats), not only due to the increased availability of salmon. However, there is a growing fear amongst traditional fishers that the decrease in price of salmon has had a detrimental effect on the prices of the traditional (wild caught) species in Europe. Until recently, the effect of this increased production on the market for traditional fish species had not been adequately studied. Instead, the focus on farmed salmon has concentrated on the supply side (for example, Steen, Asche and Salvanes 1997, MacAvinchey, Clay and Lee 1998), while the effects and implications of market interactions of salmon aquaculture have mainly been linked only to wild salmon fisheries (Wright and Copes 1992). Salmon's potential interactive effects with other species are, however, clearly evident. In France, commercial fishers blamed increased imports of salmon as the cause of falling prices of other species (Le Grel, Corre and Tuncel 1998). The UK Seafish Industry Authority has also recently commissioned a study of the effects of the increase in salmon supply on the price of other fish species in the UK.

Market interactions between salmon and the traditional wild caught species may have implications on the management of both wild caught and farmed species. Anderson (1995) demonstrated that, in an unregulated fishery, farmed production of a specie that is also harvested in a capture fishery could result in lower effort levels in the fishery, lower prices and an overall increase in supply of the product on the market. Ye and Beddington (1996) extended this analysis to consider a specie that interacts as a substitute on the market (rather than an identical product). They found similar results to Anderson (1995), except that the effects were less pronounced for a substitute specie than for an identical product.

The studies of Anderson (1985) and Ye and Beddington (1996) were largely hypothetical, and were based on a single specie capture fishery that was unregulated. In most fisheries, however, the interactions are more complex than those assumed in the earlier studies. Few fisheries are based on a single species. More commonly, fisheries are based on a set of species, with different gear types catching different combinations of species. As a result, the species interact technically, in that the catch composition is, *ceteris paribus*, a function of the gear used. In such multispecies multigear fisheries, the level of effort will depend on the prices received for the different species and the relative costs of operating the different gears. The wild caught species may also interact on the market, with many being possible substitutes. As a result, the effects of the market interactions with farmed species may be negated or enhanced depending upon the interactions (both technical and market) with the other species. In particular, the effects of the market interactions on the yield from the wild caught fishery will depend on the relative importance of the species in the overall revenue from fishing. Changes in the price of a specie that forms only a relatively small portion of the catch may have little impact on the level of effort and the resultant level of harvest in the capture fishery. The potential impact of the market interactions can be further reduced or enhanced by the form of management which is in place in the fishery.

In this paper, market interactions between salmon and the key species landed from the North Sea demersal fisheries are considered. The effects of these interactions on the potential profitability and sustainability of the fishery are examined through the use of a bioeconomic model. Simultaneously, the effects of the market interactions on the future production of salmon are also considered. The model takes into consideration the existing management measures that are in place in the fishery. The market interactions affect the prices of the species, which subsequently affect profits, effort levels and production levels.

Salmon and the North Sea demersal fishery

Salmon production

Production of farmed Atlantic salmon in the European Economic Area (EEA, which includes Norway) increased from about 27 Kt to 388 Kt between 1984 and 1996 (Steen, Asche and Salvanes 1997). In 1996, 75 per cent of the production was from Norway, with the UK (predominantly Scotland) contributing a further 21 per cent.

This large increase in production was accompanied by a decrease in the price received. Prices received by producers declined by over 60 per cent during the period 1992 to 1995 (Steen, Asche and Salvanes 1997). However, production costs over the same period declined by a larger percentage, resulting in producer profits being maintained over the period.

The main market for salmon produced in the EEA is Europe. Between 70 and 80 per cent of salmon produced in Norway, and most of that produced in the UK, is consumed within Europe. While total consumption of fish products in Europe is uncertain, salmon accounts for about 25 per cent of all fish trade within Europe, second only to cod.

The North Sea demersal fisheries

For capture fish species, the North Sea (ICES Divisions IVa,b,c - see Figure 1) is the major fishing area in European Community waters. Over half of the combined total allowable catches of all species in all EU waters are taken from the North Sea. Based on the total allowable catches (TACs) and the guide prices for each species, the total value of the allowable catch in 1999 is estimated to be about 1.4 billion Euro (Table 1). This is an underestimate of the true value of landings as the guide prices are generally lower than market prices. However, it provides an indication of the order of magnitude of the value of the fishery. Commercial activity in the region is mostly undertaken by fishers from the countries bordering the North Sea (i.e. UK, Denmark, The Netherlands, France, Germany, Belgium and Norway[1]).

[1] Norway is not a member of the European Union (EU). However, it has a significant impact on the North Sea fisheries and has entered into formal agreements with the EU for management of the fisheries.

Figure 1. ICES areas

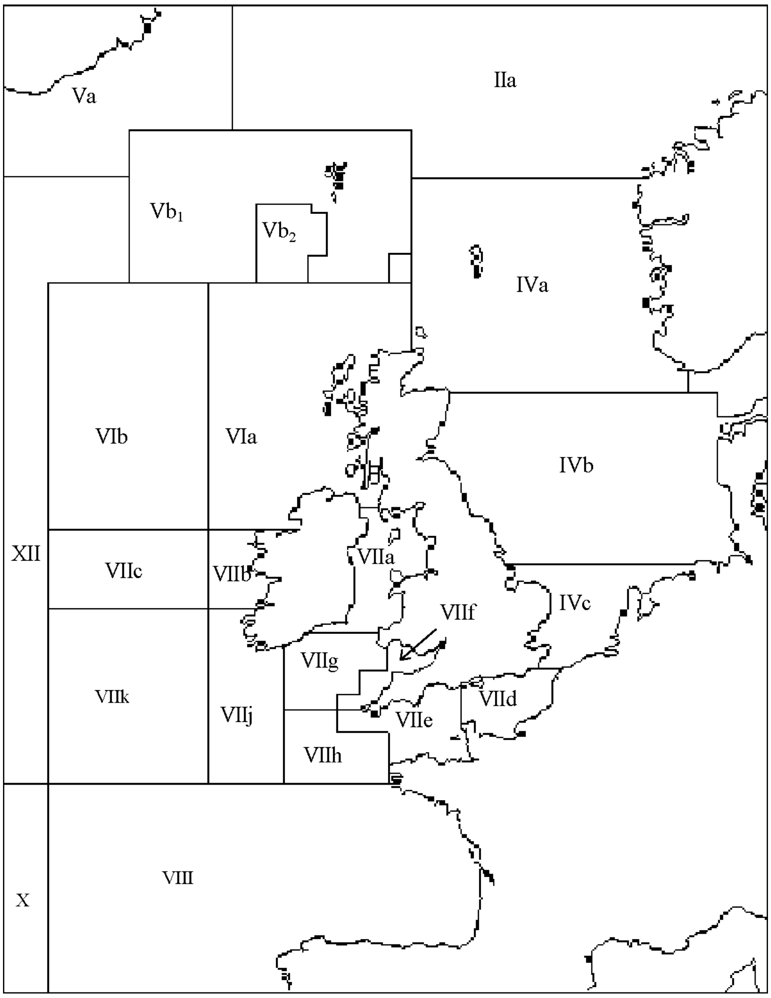


Table 1: TAC allocation for North Sea species[a] (kt) and estimated value[b] (mEuro), 1999

	Belgium	Denmark	France	Germany	Nether-lands	Norway	UK	Total	Value
Demersal groundfish[c]									
• Cod	4.7	23.9	4.9	12.1	13.1	12.5	52.4	132.4	197.4
• Haddock	0.8	5.2	5.8	3.3	0.4	14.9	56.0	88.6	90.9
• Whiting	1.2	4.9	8.2	1.4	3.0	4.4	20.9	44.0	38.9
• Saithe	0.1	2.3	13.3	6.5	0.0	57.2	4.5	110.0	84.7
Demersal flatfish									
• Plaice	6.1	14.9	0.6	6.1	46.6	3.4	23.8	102.0	132.9
• Sole	1.6	1.1	0.3	1.2	14.9	0.0	0.9	20.3	131.0
Invertebrates									
• *Nephrops*	0.8	0.8	0.0	0.1	0.4	0.0	12.9	15.2	79.5
Other								1688.4	704.7
Total								2200.9	1460.0

a) Allocation by country based on historical shares of TAC b) Values based on guide prices for 1999
c) includes ICES Division IIa for some species

The fishing activity relevant to human consumption is concentrated on nine species; cod, haddock, whiting, saithe, plaice, sole, *Nephrops* species, mackerel and herring. The first seven species are demersal species (i.e. bottom dwelling) whereas mackerel and herring are predominantly pelagic species (i.e. most usually found in mid-water). Hence, the fishing operations for mackerel and herring are usually different from those of the other species. The roundfish stocks of cod, haddock and whiting are heavily fished with approximately 60 per cent of their exploitable biomass removed each year, making the fishery very dependent upon variations in the level of recruitment. Stocks of most species are below the level that produces either the maximum sustainable yield or the maximum economic yield. The species are dependent on each other, with considerable interaction in the food chain (ICES 1996).

All of these species have annual TACs imposed by the EC under the Common Fisheries Policy and under agreement with Norway. The distribution of 1999 TACs for the North Sea of the seven main demersal species to the seven main countries is shown in Table 1. At the time of inception (1983), the method of quota definition amongst the EU Member States was based on three main factors: historic catch, compensation for loss of catches in EEZs and sensitive fishing regions. North Sea TACs are assigned on the basis of fixed proportions of each species TAC for each country.

The bycatch of other species varies with fishing gear and country. For example, turbot is an important bycatch species for Danish trawlers, while monk and anglerfish are important bycatch for French and UK trawlers. Similarly, Greenland halibut and redfish are important bycatch species for Norwegian trawlers (Concerted Action 1998).

Existence of market interactions

The empirical evidence for the existence of market interactions between salmon and wild caught species in Europe is mixed. Market delineation analysis in France (Tuncil and Le Grel 1999) and the UK (Clay and Fofana 1998) suggest that salmon may form part of the same market as (some) other wild caught species, and hence may be a substitute. A weak interaction between salmon and several key species on the Spanish market (e.g. whiting, tuna and hake) was also found (Jaffry et al 1998). However, demand analyses of the UK and Spanish markets have not found a significant interaction between the farmed and wild caught species (Clayton and Fofana 1999, Jaffry et al 1999).

At the EU level, a mix of complementary and substitute relationships was found between salmon and several wild caught species. Asche and Steen (1999) developed an AIDS model that included salmon and the seven main demersal species caught in the North Sea. The model was based on trade data as it was not possible to develop a comprehensive data set on EU demand for fish species over any appreciable time period.

The compensated elasticities estimated by Asche and Steen (1999) are presented in Table 2. The results seem to suggest that salmon may be a weak complement for some species (e.g. sole, saithe, plaice and whiting) and weak substitute for others (e.g. cod, haddock, and Nephrops). However, the elasticity estimates are potentially problematic, as significant complementary relationships were found where there were *a priori* expectation for either substitution or no interactions (e.g. whiting with haddock, plaice and Nephrops). Further, a significant positive own price elasticity was found for whiting, and a non-significant own price elasticity found for salmon.

Given these results and those of the other studies cited above, the extent of the demand interaction between salmon and wild caught species is unclear. However, managers need to be able to factor potential demand interactions into their policy decisions. With such a large number of potential interactions, not just between salmon and wild caught species but also between the different wild caught species, some form of bioeconomic model is required. Such a model is described in the following section.

Table 2 Estimated compensated elasticities, salmon and North Sea species

	Equation:							
	Cod	Haddock	Sole	Saithe	Plaice	Nephrops	Whiting	Salmon
Cod	-0.771*	0.054	1.126*	0.284	1.379*	0.457	4.010*	0.244
	(0.160)	(0.616)	(0.247)	(0.248)	(0.464)	(0.381)	(0.832)	(0.153)
Haddock	0.003	-1.032*	0.161*	0.510*	-0.048	-0.079	-1.199*	0.010
	(0.039)	(0.365)	(0.065)	(0.115)	(0.132)	(0.102)	(0.334)	(0.020)
Sole	0.224*	0.498*	-1.091*	-0.137	-0.263	0.310	0.524	-0.067
	(0.049)	(0.201)	(0.153)	(0.100)	(0.185)	(0.162)	(0.378)	(0.047)
Saithe	0.041	1.141*	-0.099	-0.489*	-0.110	0.046	0.631	-0.052*
	(0.035)	(0.257)	(0.072)	(0.162)	(0.140)	(0.105)	(0.356)	(0.023)
Plaice	0.169*	-0.091	-0.163	-0.094	-0.256	0.288	-2.181*	-0.102*
	(0.057)	(0.251)	(0.114)	(0.119)	(0.271)	(0.165)	(0.429)	(0.041)
Nephrops	0.063	-0.171	0.217	0.045	0.325	-1.065*	-0.531	0.031
	(0.053)	(0.220)	(0.112)	(0.102)	(0.187)	(0.234)	(0.387)	(0.046)
Whiting	0.109*	-0.505*	0.071	0.119	-0.481*	-0.103	1.119*	-0.098*
	(0.022)	(0.140)	(0.051)	(0.067)	(0.095)	(0.075)	(0.303)	(0.016)
Salmon	0.160	0.106	-0.223	-0.237*	-0.546*	0.145	-2.374*	0.035
	(0.100)	(0.206)	(0.156)	(0.105)	(0.218)	(0.219)	(0.391)	(0.155)

*indicates significant at a 5% level. Figures in parentheses are standard errors. Source: Asche and Steen (1999)

The bioeconomic model

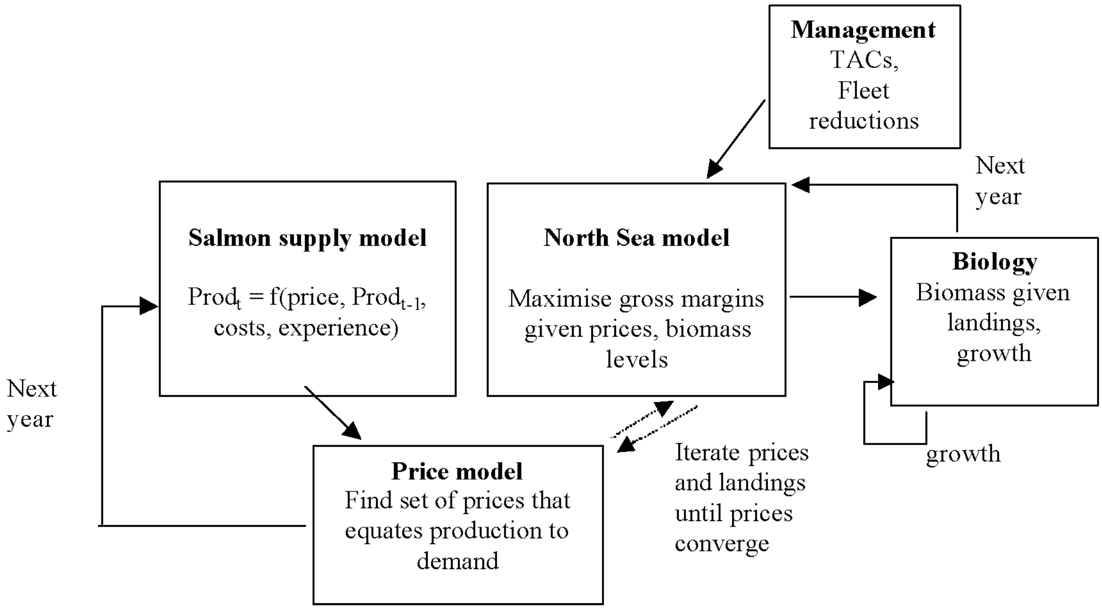
Compared with many fisheries around the world, considerable attention has been devoted to the development of bioeconomic models of the North Sea fisheries, reflecting the relative importance of the area to the EU.

A number of models have been developed for a single or limited range of species in the region. Bjørndal and Conrad (1987) and Bjørndal (1988, 1990) developed a model of the North Sea herring fishery that included a fleet dynamics function. This allowed for changes in fleet size but not in fleet structure. Dol (1996) developed a simulation model of the flatfish (sole and plaice) fishery in the North Sea, primarily for the Dutch beam trawl fleet.

A number of multi-species models have also been constructed. Kim (1983) developed a surplus production multispecies model of the demersal fishery to estimate the potential economic rent that could be achieved. Frost et al. (1993) developed two bioeconomic models of the North Sea fishery; a linear programming model and a larger simulation model to estimate levels of effort and catches. Mardle et al (1997) developed a multi-objective long run equilibrium model of the fishery which was used to estimate the optimal level of catch taking into consideration the multiple objectives of the Common Fisheries Policy. The analysis looked at trade-offs between sustainable levels of employment, discarding and fishery profitability in a long run equilibrium setting.

The model developed in this study consists of a number of separate components (Figure 2), but essentially contains three separate sub-models. These sub models represent salmon production, the demersal capture fishery in the North Sea, and the demand for the different fish products in the EU. Fisheries management measures and stock dynamics are also integrated into the model. A description of the sub-models is given below. The model was developed using the General Algebraic Modelling System (GAMS) (Brooke, Kendrick and Meeraus 1994).

Figure 2: Diagrammatic representation of the model



The salmon sub-model

The salmon production model was estimated by Steen, Asche and Salvanes (1997), and relates to Norwegian production only. An assumption is made that changes in Norwegian production are representative of changes in farmed salmon production in the European Economic Area. Given the dominance of Norway as a producer in the EEA, the assumption is likely to be fairly valid.

Salmon production in year *t* is estimated to be a function of the price in the previous year, the cost of production, production in the previous year and the cumulative production over time. The latter variable represents the efficiency improvements derived from increased experience. The model is given by:

$$\ln Q_t^s = \alpha + \beta_1 \ln P_{t-1}^s + \beta_2 \ln C_t^s + \beta_3 \ln Q_{t-1}^s + \beta_4 \ln \sum_{t^*=0}^{t-1} Q_{t^*}^s \qquad (1)$$

where Q_t^s is the production of salmon in time *t*, P_t^s is the price of salmon in time *t*, C_t^s is the average cost of production in time *t*, and α and the βs are estimated coefficients. The cost of salmon production in the model is assumed constant over the simulation period. However, the efficiency improvement component of the model (represented by cummulative salmon production) implicitly represents the decrease in costs per unit of output over time[2]. Full details of the model estimation are given in Steen, Asche and Salvanes (1997).

The North Sea sub-model

The North Sea model was based on the earlier model developed by Mardle et al (1999). The original model was based on 1994 cost, price and fleet information. These were updated to 1997 values, the most recent year where the required data were available for all countries. The updated data used in the model were taken from Pascoe *et al* (1999). Additional management measures were also incorporated into the model.

The model incorporates the main fleet segments operating in the fishery. The fleet segment is defined by country of origin and gear used. The countries included in the model are Belgium, Denmark, France, Germany, Netherlands, Norway and the UK. The gear types represented in the model include otter trawl, Danish seine, beam trawl, Nephrops trawl and gillnets. The model also includes the main demersal species landed in the fishery (cod, haddock, whiting, saithe, plaice, sole and nephrops). Bycatch of other species are incorporated into the model on an average catch per day basis.

The sub-model has two components. An optimisation component is used to estimate the level and distribution of effort each year (and the resultant catch and landings of the individual species). A dynamic simulation component is used to estimate the stock size for the next year based on the existing stock size, the natural growth in the stock and the level of catch in the previous year. The effects of existing fisheries management policies are also incorporated through the dynamic simulation component.

The optimisation component

The optimisation model was run separately for each year of the simulation. For simplicity, the subscript representing year (i.e. *t*) is not used. Endogenous variables are presented in upper case and exogenous variables (and parameters) in lower case.

The objective function for the optimisation model was the maximisation of gross margins. This is a short term profit maximising condition, expressed as

$$GM = \sum_j \sum_k \left(REV_{j,k}(1 - cs_{j,k}) - vc_{j,k} DAYS_{j,k} \right) \quad (2)$$

where GM is the total fishery gross margin, $REV_{j,k}$ is the total revenue of the boats using gear type *k* from country *j* (i.e. a given fleet segment in the fishery), $cs_{j,k}$ is the crew share for the fleet segment, $vc_{j,k}$ is the average running cost per day of boats in each fleet segment and $DAYS_{j,k}$ is the total number of days expended by the fleet segment.

The revenue of each fleet segment was given by

$$REV_{jk} = \sum_i \left(p_{j,i} LAND_{jki} \right) + vby_{j,k} DAYS_{j,k} \quad ,\forall j,k \quad (3)$$

where $p_{j,i}$ is the average price of species *i* in country *j*, $LAND_{j,k,i}$ is the total landings of species *i* by each fleet segment, and $vby_{j,k}$ is the average value of other (bycatch) species landed each day. Price was assumed exogenous in the optimisation model. An endogenous price would result in increased discarding of some species in order to

[2] For example, as $\beta_2 < 0$ and $\beta_4 > 0$, $-\beta^* \ln\left[C^s \Big/ \sum_{t^*=0}^{t-1} Q^s_{t^*} \right]$ decreases as *t* increases.

increase the overall prices of the other species[3]. However, the harvest model interacts with the price model. As will be discussed further below, the two models iterate until prices are consistent with the changes in landings in the capture model. Consequently, prices are in-effect endogenous, but are exogenous in any given iteration.

The level of landings of each fleet segment is a function of the catch of each fleet segment and the total allowable catch (TAC) for the country, such that

$$\sum_k LAND_{jki} \leq tac_{i,j} \quad ,\forall i,j \tag{4}$$

$$LAND_{j,k,i} \leq CATCH_{j,k,i} \quad ,\forall j,k,i \tag{5}$$

where $tac_{i,j}$ is the total allowable catch of species i in country j, and $CATCH_{j,k,i}$ is the catch of species i by each fleet segment. As the species are caught jointly, the catch may exceed the TAC, but landings may not exceed the TAC. The difference between $CATCH_{j,k,i}$ and $LAND_{j,k,i}$ represents discards.

An additional landing constraint was imposed representing the capacity constraint on the boats. This was to prevent an optimal solution with a small number of boats landing an impossibly large catch. The constraint was represented by

$$\sum_i LAND_{jki} + qby_{j,k} DAYS_{j,k} \leq cap_{j,k} BOATS_{j,k} \quad ,\forall i,j \tag{6}$$

where $qby_{j,k}$ is the quantity of bycatch landed by the boats on an average per day basis, $cap_{j,k}$ is the annual capacity of a boat (based on historical landings) in each fleet segment and $BOATS_{j,k}$ is the number of boats in each fleet segment.

The catch of each fleet segment was given by

$$CATCH_{j,k,i} = q_{j,k,i} DAYS_{j,k} biomass_i \quad ,\forall j,k,i \tag{7}$$

where $q_{j,k,i}$ is the catchability coefficient, and $biomass_i$ is the biomass in the year of the optimisation. As with price, this is exogenous to the model in any one year, but is endogenous between years (as outlined below).

The total days at sea of each fleet segment is a function of the number of boats in the fleet segment, given by

$$DAYS_{j,k} \leq sea\_days_{j,k} BOATS_{j,k} \quad ,\forall j,k \tag{8}$$

where $sea\_days_{j,k}$ is the average number of days at sea of boats in each fleet segment. The number of $BOATS_{j,k}$ was constrained to be less than or equal to the existing (1997) number of boats in each fleet segment. This upper bound is modified each year to take into account the effects of existing management policies (as will be seen below)

Given the fleet size, level of effort and landings, the level of financial and economic profits could be estimated. In addition, the total employment in the fishery could also be estimated. These are given by

$$FPROF_{j,k} = REV_{j,k}(1 - cs_{j,k}) - (fc_{jk} BOATS_{j,k} + vc_{jk} DAYS_{jk}) \quad ,\forall j,k \tag{9}$$

[3] This behaviour was noted in earlier versions of the model, and required the separation of the price model from the harvest model.

$$EPROF_{jk} = FPROF_{jk} - (dep_{j,k} + occ*kval_{j,k})\text{BOATS}_{j,k} \quad ,\forall j,k \tag{10}$$

$$TFPROF = \sum_j \sum_k FPROF_{j,k} \tag{11}$$

$$TEPROF = \sum_j \sum_k EPROF_{j,k} \tag{12}$$

$$EMPLOY = \sum_j \sum_k crew_{j,k} BOATS_{j,k} \tag{13}$$

where $FPROF_{j,k}$ and $TPROF$ are the financial profit at the fleet segment and total fishery level respectively; $EPROF_{j,k}$ and $TEPROF$ are economic profits at the fleet segment and fishery level respectively; and $EMPLOY$ is the total employment in the fishery. Financial profits take into account both variable and fixed costs ($fc_{j,k}$). Economic profits also take into account the non-financial costs such as depreciation ($dep_{j,k}$), the opportunity cost of capital (*occ*, expressed as a percentage of total capital) and the capital value of the boats ($kval_{j,k}$). Total employment is a function of the average crew number ($crew_{j,k}$, including skipper) and the total number of boats.

Although the objective is to maximise gross margins, an additional constraint is imposed in the model that the financial profits of each fleet segment participating in the fishery must be either zero or positive. Most of the boats in the fishery are able to operate in adjacent fisheries, and it is assumed they would move to these fisheries if they could not cover all of their fixed and variable costs.

The dynamic simulation component

The dynamic simulation component of the model takes into account changes in biomass, and changes in restrictions on catches and boat numbers arising from existing management policies.

Although biomass is taken as given in any particular year in the optimisation model, the biomass is estimated between the years as a function of the level of biomass and harvest in the previous year. The stock dynamics in the model take the simple form

$$B_{i,t+1} = B_{i,t} + G_{i,t} - \sum_j \sum_k CATCH_{i,j,k} \tag{14}$$

where $B_{i,t}$ is the biomass of specie i in time period t, and $G_{i,t}$ is the surplus growth of species i in period t. The demersal species included in the model interact with each other to a considerable degree. The increased stock of one species may displace another, while some species consume others to some extent (ICES 1996). The predator/prey/competition features of the fishery were included using multispecies logistic growth models of the form:

$$G_{i,t} = r_i B_{i,t} \left(1 - \frac{B_{i,t}}{\sum \beta_{s_i^{'}} B_{s_i^{'},t} + K_i} \right) - \sum \alpha_{s_i} B_{s_i,t} \tag{15}$$

where G_i is the growth of species i, r_i is the growth rate, K_i is the environmental carrying capacity (excluding the effects of the modelled prey species), B_i is the biomass, $s_i \in S_i$ is the set of predator species and similarly $s_i^{'} \in S_i^{'}$ is the set of prey species.

Details on the estimation of these multi-species growth models are given in Mardle et al (1999).

The estimated new value of the biomass of each species replaces the previous estimate of $biomass_i$ in the optimisation model for the next year's simulation.

The fishery is subject to management through both input controls and output controls. Total allowable catches are determined each year on the basis of scientific advice regarding the state of the stocks. Although the actual TAC setting process is complex, and takes into consideration political and social factors, the change in the TAC generally reflects the change in the biomass. In the model, it was assumed that the TAC of each species would change in proportion to the change in biomass, such that

$$TAC_{i,j,t} = \frac{B_{i,t}}{B_{i,t-1}} TAC_{i,j,t-1} \qquad (16)$$

The estimated new TAC replaces the previous value of tac_i in the optimisation for the next year's simulation.

The fishery is also subject to fleet reductions through the Multi-Annual Guidance Programme (MAGP). The objective of the MAGP is to reduce fleet capacity to bring it in line with the regenerative capacity of the stocks. The programme operates over a five year period, with explicit effort reduction targets for different fleet segments. The current (fourth) MAGP operates over the period 1997-2002. It was assumed for the purposes of the model that a similar rate of effort reduction would be required after 2002.

The effect of the MAGP is to reduce the maximum number of boats that can operate in each fleet segment. In the model, this maximum is reduced each year based on the annualised rate of decrease for each fleet segment, given by

$$MAXBOATS_{j,k,t} = (1 - magp_{j,k}) MAXBOATS_{j,k,t-1}, \ \forall j,k \qquad (17)$$

where $MAXBOATS_{j,k,t}$ is the maximum number of boats in each fleet segment in period t, and $magp_{j,k}$ is the annualised percentage reduction in boat numbers in each segment.

The price sub-model

The price sub-model uses the elasticity estimates of Asche and Steen (1999) to estimate the set of prices that equate changes in supply with changes in demand. The sub-model is formulated as a goal programming problem, where deviations from objective values are minimised.

A key objective of the sub-model is to minimise inequality between supply and demand for both salmon and the wild caught species. An assumption is made that change in supply from salmon and wild caught species is equal to changes in demand. The relationship between changes in demand and changes in prices for the wild caught species may be represented as

$$\frac{\sum_j \sum_k LAND_{i,j,k} - base97_i}{base97_i} = \sum_{i*} \varepsilon_{i,i*} \frac{PSCALE_{i*} - 1}{1} + \varepsilon_{i,s} \frac{SSCALE - 1}{1} + N1_i - P1_i, \quad \forall i \tag{18}$$

where $base97_i$ is the observed landings in 1997, $\varepsilon_{i,i*}$ is the elasticity of demand (own price elasticity if $i=i*$, cross price if $i\neq i*$), $PSCALE_{i*}$ is the price scaling factor for species i*, $\varepsilon_{i,s}$ is the cross price elasticity of demand between salmon and species i, and $N1_i$ and $P1_i$ are positive and negative deviational variables respectively.

Similarly, the relationship between changes in demand and price for salmon is given by

$$\frac{Q_t^s - Q_{96}^s}{Q_{96}^s} = \sum_i \varepsilon_{s,i} \frac{PSCALE_i - 1}{1} + \varepsilon_{s,s} \frac{SSCALE - 1}{1} + N2 - P2 \tag{19}$$

where Q_{96}^s is the base level of salmon production in 1996, $\varepsilon_{s,i}$ is the cross price elasticity between salmon and the other species, $\varepsilon_{s,s}$ is the own price elasticity for salmon, and $N2$ and $P2$ are negative and positive deviational variables.

As the elasticities are point estimates, their accuracy deteriorates with large deviations from the original prices. Given that multiple combinations of prices may satisfy the supply and demand conditions, the preferred combination is that which deviates least from the base prices. The additional objectives were included that

$$1 = PSCALE_i + N3_i - P3_i, \quad \forall i \tag{20}$$
$$1 = SSCALE + N4 - P4 \tag{21}$$

where $N3_i$ and $N4$ are negative deviational variables and $P3_i$ and $P4$ are positive deviational variables.

The achievement function to be minimised in the price sub-model is given by

$$\min Z = w_1 \left[\sum_i (N1_i + P1_i) + (N2 + P2) \right] + w_2 \left[\sum_i (N3_i + P3_i) + (N4 + P4) \right] \tag{22}$$

where w_1 and w_2 are the weights associated with the different objectives. Greater weight was given to the objectives balancing changes in prices with changes in landings and production.

Interaction between the sub-models

The salmon production sub-model was based on prices in the previous year. As a result, the production from the salmon sub-model was passed directly to the price sub-model. For the wild caught species, the level and distribution is a function of revenue, and hence is affected by the prices received. In turn, the level of landings of each species affects the prices. Within each year of the simulation, the harvest and price sub-models are iterated (i.e. run within a recursive loop). The previous year's prices are used to obtain the first estimate of landings. These are passed to the price sub-model and the new prices estimated. These are passed back to the harvest model and a new set of landings estimated. The process continues until the prices converge (i.e. do not change from one iteration to the next by more than a specified amount, in this case 5 per cent). This then provides the final estimates of prices and landings for the year. Biomass, quotas and maximum fleet numbers are then estimated for the following year, along with the salmon production.

Model simulations and results

Given the uncertainty regarding the market interaction between salmon and the other species in the model, three scenarios were examined. The first scenario was that salmon was a weak substitute for the other species; the second that salmon did not interact with the other species; and finally that salmon was a weak complement for some of the species and a substitute for others (i.e. mixed interactions). The elasticity estimates in Table 2 were modified to allow for these possibilities. In all cases, cross price elasticities that suggested that the wild caught species were complements were set to zero. To maintain homogeneity in the system, the own price elasticities were adjusted to ensure that the sum of the elasticities was equal to zero for each species. As the substitute species had positive cross price elasticities, the effect of removing the negative cross price elasticities was to make the own price elasticity more elastic (i.e. more negative).

In the simulation where salmon was considered a weak substitute, the negative cross price elasticities between salmon and the other species were also set to zero, and the own price elasticities adjusted to ensure homogeneity. For the simulations where salmon was considered a weak complement, the negative cross price elasticities between salmon and the other species given in Table 2 were retained. For the simulation involving no interaction between salmon and the wild caught species, homogeneity in the salmon price model could not be achieved unless the own price elasticity for salmon was zero. As this is not realistic, an own price elasticity of –0.999 was assumed, based on previous single equation estimates of the own price elasticity of salmon[4]. A summary of the modified elasticity estimates used in the analyses is given in Table 3. Other elasticities (with the exception of the negative cross price elasticities for the wild caught species) used in the model were as given in Table 2.

Table 3. Modified elasticities used in the analyses

	Weak substitute			No interaction			Mixed interactions		
	Own price	Salmon on fish	Fish on salmon	Own price	Salmon on fish	Fish on salmon	Own price	Salmon on fish	Fish on salmon
Cod	-0.771	0.162	0.244	-0.609	0	0	-0.771	0.162	0.244
Haddock	-1.299	0.106	0.01	-1.193	0	0	-1.299	0.106	0.01
Whiting	-0.5	0	0	-0.5	0	0	-0.5	0	-0.098
Saithe	-0.913	0	0	-0.913	0	0	-0.675	-0.238	-0.052
Plaice	-1.304	0	0	-1.304	0	0	-0.758	-0.546	-0.102
Sole	-1.575	0	0	-1.575	0	0	-1.354	-0.221	-0.067
Nephrops	-1.139	0.145	0.031	-0.994	0	0	-1.139	0.145	0.031
Salmon	-0.285	-	-	-0.999	-	-	-0.034	-	-

The model was run over an 11 year period. The first year of the simulation represented 1997. The purpose in this was to see how well the model estimated catches in that year, and to assist in the calibration of the model[5]. After calibration, the differences between actual 1997 catches and those estimated using the model were less than 1 per cent. The

[4] Bjørndal, Gordon and Salvanas (1992) reported estimates of own price elasticity of salmon ranging from –0.62 to –1.83 within Europe.

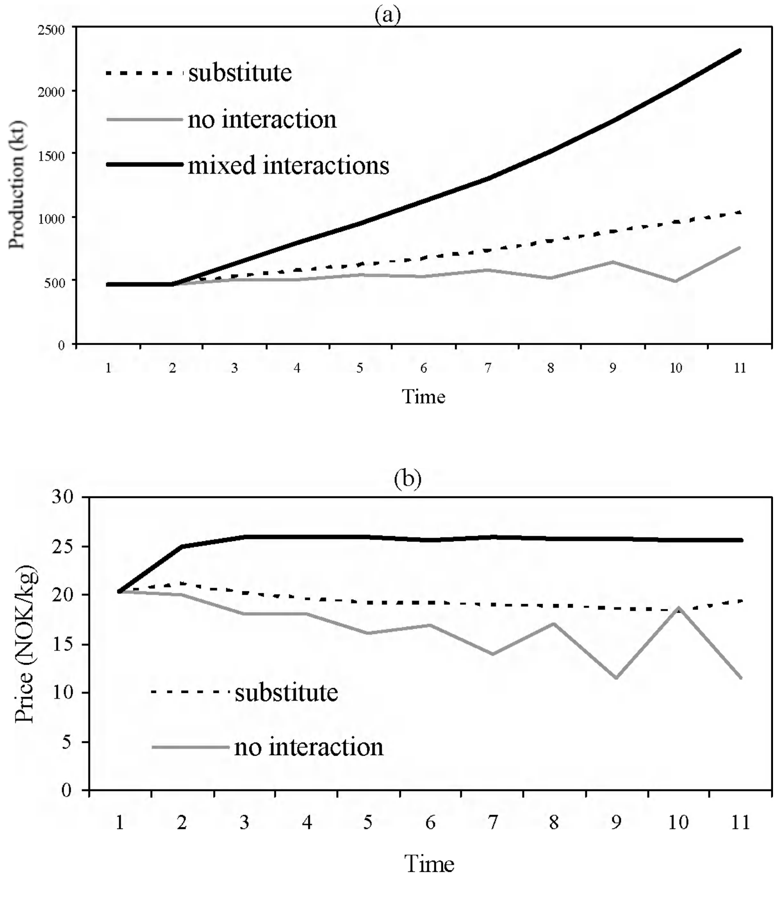
[5] This involved adjusting the catchability coefficient for some fleet segments where estimated catches diverged substantially from known catches given the fleet size and structure and biomass.

model was run for a further 10 years to examine the effects of the interactions. The results of the model are not predictive, as they do not take into account all factors that affect the fishery (e.g. environmental fluctuations that may affect the biomass or catch, exchange rate fluctuations that may affect the prices or costs). Similarly, management may not necessarily respond in the manner incorporated into the model, as higher or lower TACs may be imposed depending on social and political factors. Consequently, the results are indicative only of the potential effects of market interactions in the fishery. Given this, relative changes rather than absolute values in any one year are of more importance when considering the results.

Salmon production and prices

The estimated effects of the interactions on the production and prices of salmon are illustrated in Figure 3. As expected, the production of salmon was estimated to continue to increase over the period examined. However, the rate of increase was greatest when salmon was assumed to be a weak complement to some of the wild caught species.

Figure 3. Estimated effects of demand interactions on a) production and b) prices of salmon



If no interaction exists, production of salmon was estimated to increase only slowly. Prices were also estimated to be lowest if no interactions exist. The estimated fluctuations in price arose as the price fell below the average cost of production, resulting in a reduction in production the following year, and a corresponding increase in price.

When a substitute relationship was assumed, the price of salmon was estimated to decline gradually over the period examined, while production was estimated to increase at a modest rate. These results are in keeping with the theoretical results of Ye and Beddington (1996), that total production would increase and prices decline when the farmed product was a substitute.

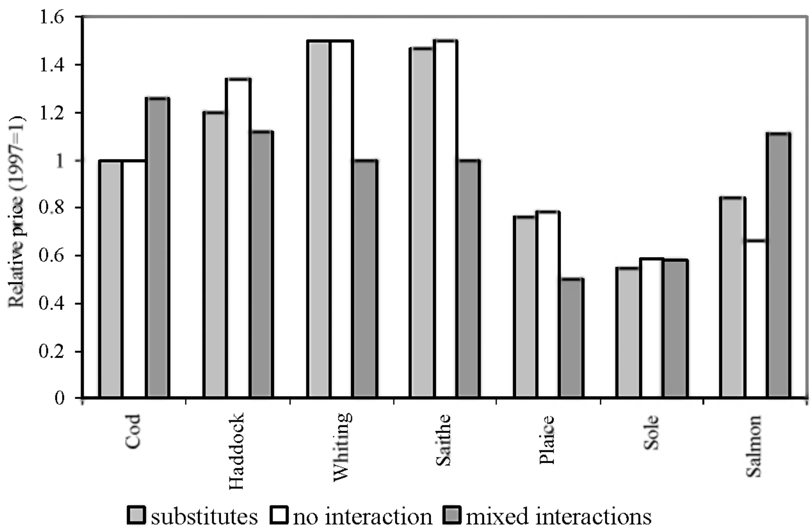
The North Sea fishery

The net present value of the estimated profits and revenue over the 11 year period of the simulations are given in Table 4. The values were discounted at 5 per cent. As would be expected, if salmon is a substitute good for the other species, then the level of profits over time would be less than if no interaction exists. This is in keeping with the theoretical work of Anderson (1985) and Ye and Beddington (1996), as the effects of the substitutability would be to generally lower price levels for the wild caught species as the production of the farmed species increased. Prices estimated using the model were generally lower at the end of the period examined when salmon was assumed a substitute compared to the case where no interaction was assumed (Figure 4).

Table 4. Net present value of key economic indicators (mEuro)

	Economic profits	Financial profits	Gross Margins	Revenue
Weak substitute	629	1,849	3,057	7,214
No interaction	782	2,002	3,214	7,452
Mixed interactions	314	1,541	2,771	6,812

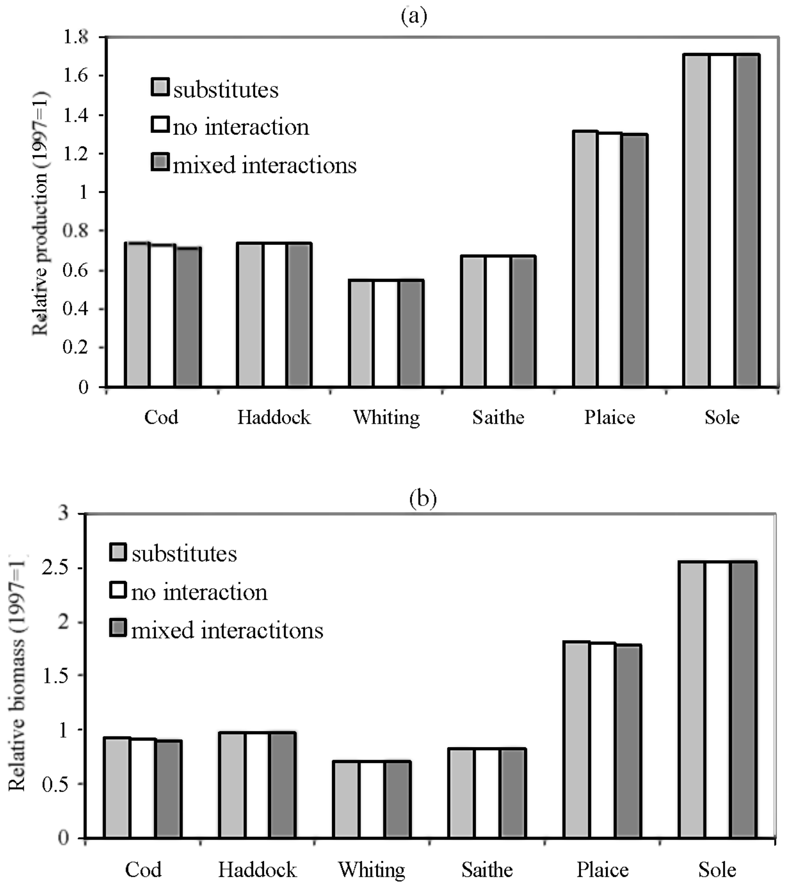
Figure 4. Estimated relative prices at the end of the simulation period



An unexpected result, however, was that if salmon is a weak complement with some species, then an even lower level of profits may result than if it was a weak substitute. This resulted from the combination of substitute and complement relationships in the model, and the negligible own price elasticity of salmon when it was assumed to be a substitute good for some species.

The differences in revenue and profits under the different scenarios were estimated to arise predominantly through changes in price. The levels of landings of the key species (and their associated biomass levels) were estimated to be largely unaffected as a result of the market interactions between the farmed and wild caught species (Figure 5). This was largely because landings were constrained by total allowable catches. Stock recovery (in the case of plaice and sole) was largely achieved as a result of fleet reductions under the MAGP.

Figure 5. Estimated relative a) landings and b) biomass of the key species in the final year of the simulation



The greater reduction in revenue and profits when salmon was assumed to be a complement with some species was a function of the own and cross price elasticities. From Table 3, the highly inelastic own price elasticity of salmon would have required a large decrease in prices to clear the market, *ceteris paribus*. However, the decrease in sole and plaice price as a result of the higher landings of these species would have helped to support the demand for salmon, increasing its price. Further, the increase in cod prices as a result of reduced cod landings would have also helped to support the salmon prices. Conversely, the resultant increase (rather than decrease) in salmon prices further reduced the demand for the complementary goods, further reducing their prices. As a result, the complementary relationship was estimated to have depressed the prices of the species where stocks were recovering (and hence landings increasing) by a greater extent than the substitute relationship increased the prices of the species where landings were declining.

These results are substantially different than those proposed by Anderson (1985) and Ye and Beddington (1996). In their models, market interactions (assumed to be competitive) resulted in a reduction in an increase in wild caught catch, higher stocks, lower prices and an overall increase in production. However, in a fishery where the biomass of some species are experiencing decline while others are experiencing growth, the results are less clear cut. Where the relationship between farmed and the increasing wild caught species is one of complementarity rather than substitution, a recovering natural stock and increase in catches may result in prices of the wild caught species declining by a greater extent than in the case of no interaction. As seen in the above example, this is especially the case if the price of the farmed species is being supported through price increases of competing species.

Discussion and conclusion

Concern was originally raised by European fishers that the increase in salmon production may depress the price of the wild caught species through substitution of farmed products for harvested products on the market. Previous studies of market interactions between salmon and the main wild caught species harvested in Europe have been inconclusive as the extent and the direction of this relationship. In most studies, salmon has been identified as, at most, only a weak substitute for a limited range of species.

From the model results, if salmon was a substitute for a number of wild caught species, then it would be expected that the increase in salmon production would result in a general decrease in prices for the competing species, other things being equal. In the analysis of the North Sea demersal fishery, the estimated decrease in price of the main competing species, cod, was limited in the simulations as cod landings were also declining, resulting in upward pressure on prices. As a result of the opposing forces, cod prices remained largely unchanged, and total revenues (and profits) were estimated to be lower than if there was no interaction between the species.

These results are broadly in keeping with the analyses of Anderson (1985) and Ye and Beddington (1996), which suggested that, given a substitution relationship between a farmed and capture species, profits in the wild caught fishery would fall, effort would decrease and stocks would recover as farmed production increases. In a multispecies fishery such as the North Sea demersal fishery, profits are not dependent on a single species. Further, the existence of management measures were already restricting the level of both landings and effort. Nevertheless, the general conclusions of the earlier studies are reasonably valid.

Recent demand analysis has raised the possibility that salmon may form a complementary relationship with some species. The interpretation of the complementary relationship, if it exists, is that the growth of salmon production may have increased the overall demand for seafood (rather than that the complementary species are consumed together). Prior to the wide-scale expansion of farmed production, salmon had been perceived as a luxury food item. Increased availability and affordability of salmon in supermarkets may have encouraged previous non-consumers of fish to try salmon. These new consumers may then have diversified onto other fish species which were also available in the supermarkets. This increase in demand, *ceteris paribus*, would be expected to increase the prices for these species.

In the North Sea fishery, however, the mix of substitute and complementary relationships with salmon may result in a greater reduction in revenue and profits than under a purely substitute relationship alone. In the simulations described above, this outcome was largely due to the unfortunate coincidence that landings of the complementary species were increasing, while landings of the substitute species were decreasing. The complementary relationship with salmon exacerbated the estimated decline in price of sole and plaice while increasing the price of salmon. In addition, increased cod prices (due to an estimated fall in landings) were estimated to be further supported by the increase in the price of salmon through the substitution relationship[6]. This result is rather

[6] Removing the substitute relationships with salmon in the model had further adverse consequences as the falling sole prices continued to support the higher salmon prices through the complementary relationship. However, without the substitution relationship with salmon, the estimated prices of cod,

unique, and had the conditions been reversed (i.e. cod landings increased and other species landings decreased or stayed the same) then the market interaction between salmon and the wild caught species may have acted to increase overall prices and profitability in the fishery.

The models of Anderson (1985) and Ye and Beddington (1996) were also applied to unregulated fisheries. In the simulations using the North Sea model, catch and biomass were affected purely by the existing fisheries management regime. While the biomass of some species was estimated to decrease over the period of the analysis, these had largely stabilised by the end of the simulation period. For other species, biomass (and catch) was estimated to have increased. Consequently, from a biological conservation perspective, the existing management policies are likely to be adequate regardless of the type of market interaction between the species.

Despite this, the potential mix of substitution and complementary relationships between salmon and the wild caught species has some interesting implications for management. It is tempting for managers to increase the total allowable catch on species that are able to sustain such an increase when catches of other species are declining. This, in theory, allows fishers to divert effort from the declining species and maintain their short-term incomes. However, such a strategy may result in an overall decline in incomes, as illustrated in the North Sea fishery example. When demand is inelastic (as is the case for plaice and saithe when assumed to be complementary to salmon), increasing supply results in an overall reduction in income, as the resultant percentage decline in price is greater than the percentage increase in supply.

From an economic perspective, restricting the landings of plaice and sole, even though the biomass could support larger landings, may have resulted in higher incomes in the fishery. For example, limiting the landings (through a TAC) of sole and plaice to their 1997 level for the whole period of the simulation resulted in the estimated price of plaice remaining relatively constant over the period, the estimated price of sole declining to a lesser extent, and the price of salmon increasing to a lesser extent. As a result, the total revenue in the fishery was estimated to be about 6 per cent higher, and economic profits almost double, than if the simple TAC rule used in the model was adhered to. Similarly, the estimated inelastic demand for cod would imply that stock recovery may also result in a decrease in incomes. Consequently, a policy of achieving the maximum sustainable yield for this species may be detrimental to the economic performance of the fleet. Thus, there is a need to consider the potential effects on prices and incomes when setting TACs.

A further alternative policy option is the limitation of the supply of salmon. The own price elasticity of salmon was also estimated to be inelastic, indicating the total revenue from salmon production would fall as production increased, *ceteris paribus*. Salmon producers may therefore benefit by limiting the level of output. This may have beneficial effects on the wild caught species, particularly for the estimated substitute species.

The results of the model analyses indicate that the simple models proposed by Anderson (1985) and Ye and Beddington (1996) are not sufficient to determine the likely effects of increased aquacultural production on prices of wild caught species and on the incomes in many real-world capture fisheries. The market interactions between the wild caught

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haddock and Nephrops did not increase to the same extent. As a result, even lower revenues and profits were estimated to occur if only a complementary relationship existed with salmon.

species in multi-species fisheries, the existence of management and the potential for complementary as well as substitute relationships results in a generally unpredictable outcome that is specific to each case examined. The development of bioeconomic models that incorporate these interactions, such as that developed in this paper, will become increasingly important to assess the potential effects of management changes, as these will depend on the demand interactions as much the biological relationships in the fishery.

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