Alternative Management Regimes for Multiple Species Fisheries

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I. Objective

The lack of an efficient property rights structure is widely recognized as the prime impediment to higher profitability of the fishing industry and to the prevention of overexploitation. Under open, i.e., free and unrestricted access to fishery resources, the potential economic rent tends to be dissipated by overfishing.(1) While the need for replacing the open access regime by a legal-institutional structure which restricts access is now widely accepted, biologists and economists differ on the choice of the appropriate criteria to be used in fishery management. In addition, aside from theoretical consideration, the practicality of either management criterion is an open question.

This study considers four alternative fishery regimes. First, the economically first-best regime with the optimality criterion of optimal sustainable yield (OSY)

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(1) The inefficiency of the open access regime has been the subject of many theoretical studies: cf. Gordon [7], Christy and Scott [4], Clark [5], and the survey of Peterson and Fisher [13]. For empirical evidence, see, for example, Bell [2].

is examined. Second, as a variant of OSY, the criterion of uniform profitability (UPY) is imposed in order to analyse what efficiency implications would be obtained if the management authority—for distributional or other reasons—would wish to follow the rule that profitability should be uniform over all species. Third, the biologically optimal fishery based on criterion of maximum sustainable yield (MSY) is evaluated. Finally, the open access regime with the bionomic equilibrium (BEY) of long run equality between revenue and cost is examined.

The paper proceeds as follows: In Section II, the optimality conditions are derived within a full dynamic context. In order to arrive at empirically operational models, the restrictive assumption of a stationary state—implying a zero social rate of discount—is imposed in Section III. Section IV presents further empirical specification. Empirical results of the model application to the multispecies fishery of the North Sea are presented in Section V. Section VI contains the conclusion and discusses the efficiency of the four alternative fishery regimes.

II. Optimality Conditions

As a renewable resource, the stock of fish is dependent on the stock's rate of reproduction, the rate of natural mortality, and the intensity of fishing. Thus, the population dynamics of a multiple species fishery with n individual species can be represented by⁽²⁾

$$\frac{dB^i}{dt}=g^i(B^i)-f^i(E^i, B^i) \qquad i=1, 2, \ldots, n \qquad (1)$$

where $g(\cdot)$ is the net natural growth of the stock, which depends on the stock size, B^i, and $f(\cdot)$ is the attrition of the stock due to fishing, which in turn depends on the stock size and on the amount of resources used in fishing,

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(2) For examples for this specification of population dynamics, see Clark [5] and Peterson and Fisher [13]. Past studies of multiple species fishery have concentrated on the implications of biological and technological interdependences (through, e.g., predator-prey or by-catch relationships): for examples, see Anderson [1], Clark [5], or Huppert [10].

the latter represented by the composite factor "fishing effort," E^i.(3)

Optimality in resource use requires maximization of its present value. With perfect competition in product and factor markets, the present value of the resource of multiple species fisheries is

$$PV=\sum_{i=1}^{n}\int_{0}^{\infty}\{p^if^i(E^i,B^i)-wE^i\}e^{-\delta t}dt \tag{2}$$

where δ is the social rate of discount, p^i is the fish price of species i, and w is the constant unit cost of fishing effort. Maximization of the present value subject to condition (1) yields the economically optimal level of fishing. This is equivalent to an optimal control problem where the Hamiltonian

$$H=\sum_{i=1}^{n}\{p^if^i(E^i,\ B^i)-wE^i\}\ e^{-\delta t}+\sum_{i=1}^{n}\lambda^i\{g^i(B^i)-f^i(E^i,B^i)\} \tag{3}$$

is maximized. The marginal user cost of species i *in situ* (the uncaught stock of i) is λ^i. For a dynamic optimum, the following necessary conditions have to be satisfied for all species:

$$H^i_E=(p^if^i_E-w)e^{-\delta t}-\lambda^if^i_E=0 \tag{4}$$

$$\begin{aligned}\frac{d\lambda^i}{dt}&=-H^i_B\\&=-(p^if^i_Be^{-\delta t}+\lambda^ig^i_B)\end{aligned} \tag{5}$$

which imply

$$\lambda^i=e^{-\delta t}\ \frac{p^if^i_Bf^i_E-\delta(p^if^i_E-w)}{f^i_E(f^i_B-g^i_B)}\ . \tag{6}$$

Substitution of (6) into (4) yields the optimal condition:

$$p^i=\frac{w}{f^i_E}+\frac{p^if^i_Bf^i_E-\delta(p^if^i_E-w)}{f^i_B-g^i_B}\ . \tag{7}$$

For the exploitation of a multiple species fishery to be at the optimal level, price has to be equal to the sum of marginal harvesting cost and marginal user cost. This has to hold for all the species involved at any given moment of time.(4)

Under competitive conditions and irrespective of the fishery management

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(3) To simplify the discussion, it is assumed here that species are biologically and technologically independent.

(4) For the case of a single species fishery, see Kim [12] for analogous conditions.

scheme (restrictive or open access), each fisherman attempts to maximize his own share of the current industrial profit. As far as fisherman j is concerned, the potential profit from fishing of multiple species is:

$$\pi_j=\sum_{i=1}^{n}\left(p^i\frac{f^i}{E^i}E^i_j-wE^i_j\right). \tag{8}$$

However, the individual fisherman j's optimization behavior is constrained by the endowment level of the production factors (the capacity to generate a flow of fishing effort):

$$\bar{E}_j=\sum^{i}E^i_j.$$

The constrained maximization of the current profit for individual fisherman j is equivalent to maximization of the Lagrangean:

$$L=\sum^{i}\left(p^i\frac{f^i}{E^i}-w\right)E^i_j+\lambda\left(\bar{E}_j-\sum^{i}E^i_j\right) \tag{9}$$

which yields as the necessary conditions for fisherman j's optimal fishery:

$$L^i_{E_j}=p^i\frac{f^i}{E^i}-w-\lambda=0 \qquad i=1,2,\ldots,n$$

$$L_\lambda=\bar{E}_j-\sum^{i}E^i_j=0.$$

They in turn imply that

$$p^i\frac{f^i}{E^i}=p^h\frac{f^h}{E^h}\ (=\text{constant}=w+\lambda),\quad i\neq h. \tag{10}$$

Under competitive conditions, the individual fisherman will attempt to allocate his given endowment of productive resources in such a way that the expected average productivity is equalized across potential fisheries of various species. In other words, by individual optimization behaviour of fishermen, the average profit (and the average revenue in the present case of constant unit cost of fishing effort) is equalized across the fishing industry.(5) This condition has to be satisfied for the private equilibrium in a multiple species fishery. In disequi-

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(5) The equilibrium condition is expressed in terms of average revenue rather than average profit, since both are equivalent under the present assumption of constant unit cost of fishing effort. Relaxation of this cost assumption does not qualitatively change the following discussions.

librium, intra-firm movements of fishing efforts will work as the equilibrating force.

As noted, under the open access the fishery tends to converge to a state of fishery where the economic rents of all respective species are completely dissipated. In the present context, this long run equilibrium is special case when the resource constraint is not binding for all fishermen involved, i.e. when $\lambda=0$. (6)

If the management authority chooses the uniform profitability as a prerequisite for the implementation of a comprehensive fishery management scheme, the management authority would then act as a constrained optimizer, i.e., maximizing the present value of the multiple species fishery resource (2) subject to the biological and private economic equilibrium conditions (1) and (10). This is equivalent to maximization of the following Hamiltonean:

$$
\begin{aligned}
H=&\sum^{i}\{p^i f^i(E^i,B^i)-wE^i\}e^{-\delta t}+\sum^{i}\lambda^i\{g^i(B^i)-f^i(E^i,B^i)\}\\
&+\sum_{h=2}^{n}\psi^h\left\{p^1\frac{f^1(E^1,B^1)}{E^1}-p^h\frac{f^h(E^h,B^h)}{E^h}\right\}.
\end{aligned}
\tag{11}
$$

The necessary conditions for a dynamic optimum fishery are:
for species 1,

$$
H_E{}^1=\left\{(p^1f^1{}_E-w)e^{-\delta t}-\lambda^1f^1{}_E+\sum_{h=2}^{n}\psi^h\frac{p^1f^1{}_E-p^1f^1/E^1}{E^1}\right. \tag{12}
$$

and for species $i\neq1$,

$$
H^i{}_E=(p^if^i{}_E-w)e^{-\delta i}-\lambda_if^i{}_E-\psi^i\frac{p^if^i{}_E-p^if^i/E^i}{E^i}. \tag{13}
$$

The corresponding adjoint equations are:
for species 1,

$$
\begin{aligned}
\frac{d\lambda^1}{dt}&=\frac{p^1f^1{}_E-w}{f^1{}_E}(-\delta)e^{-\delta t}\\
&=-H^1{}_B=-e^{-\delta t}p^1f^1{}_B-\lambda^1(g^1{}_B-f^1{}_B)-\sum_{n=2}^{n}\psi^n\frac{p^1f^1{}_B}{E^1}
\end{aligned}
\tag{14}
$$

and in the case of species i ($\neq1$),

$$
\frac{d\lambda^i}{dt}=\frac{p^if^i{}_E-w}{f^i{}_E}(-\delta)e^{-\delta t}.
$$

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(6) This study adopts the specification of Peterson and Fisher [13] for the discussion of the fishery under competitive conditions.

$$=-H^i{}_B=-e^{-\delta t}p^i f^i{}_B-\lambda^i(g^i{}_B-f^i{}_B)+\psi^i\frac{p^i f^i{}_B}{E^i}. \tag{15}$$

The resulting optimum conditions are:

for species 1,

$$\Delta^1 e^{-\delta t}=\phi^1\sum_{h=2}^{n}\psi^h \tag{16}$$

where

$$\Delta^1=p^1 f^1{}_E-w-\frac{p^1 f^1{}_B f^1{}_E-\delta(p^1 f^1{}_E-w)}{f^1{}_B-g^1{}_B}$$

$$\phi^1=\frac{1}{E^1}\left(p^1\frac{f^1}{E^1}-p^1 f^1{}_E+\frac{p^1 f^1{}_B f^1{}_E}{f^1{}_B-g^1{}_B}\right)$$

and for species $i(\neq 1)$,

$$\Delta^i e^{-\delta t}=\phi^i\psi^i \tag{17}$$

where Δ^i and ϕ^i retain the same functional forms as Δ^1 and ϕ^1. Conditions (16) and (17), when combined, imply that

$$\sum^{i}\frac{\Delta^i}{\phi^i}=0. \tag{18}$$

Together with the equilibrium condition (10), (18) completes the set of necessary conditions and provides a unique solution for the dynamic optimum fishery of multiple species resource. The dynamic optimum when the equilibrium constraint (7) is not binding, is a special case to the dynamic optimum (18), i.e., for all species i $(i=1, 2, \ldots, n)$,

$$\Delta^i=0.$$

The immediate implication of the above constrained optimum condition (18) is that if a fishery resources with multiple species is managed in such a way that the private economic equilibrium is not disturbed, some species should be managed beyond the level of independent economic optima while other species are managed below the level of their own optima, and furthermore that the degree of these divergencies should be exactly offset among the species. Second, even if species are independent each other in a technological (e.g., by-catch) and biological (e.g., predator-prey) sense, they are economically related to each other in a competitive fishery.

III. Model

For the empirical specification of the fishery population dynamics (1), it is assumed that, in the absence of fishing, the stock grows according to a logistic growth curve:

$$g^i(B^i)=a^iB^i(B^i_m-B^i) \qquad i=1, 2, \ldots, n \tag{19}$$

where B^i_m is the maximum stock size of species i under prevailing environmental conditions, and that the catch is of a mass-contact function:

$$f^i(E^i, B^i)=q^iE^iB^i. \tag{20}$$

Combination of (19) and (20) leads to the empirical specification of population dynamics of the so called "surplus production" model:(7)

$$\frac{dB^i}{dt}=a^iB^i(B^i_m-B^i)-q^iE^iB^i. \tag{21}$$

The biological equilibrium condition requiring a balance between the net growth and the fishing mortality, i.e., $dB^i/dt=0$, yields the steady state relationship between catch, C^i, and fishing effort (the sustainable catch-effort relationship)(8) which can be simplified as

$$C^i=\alpha^iE^i-\beta^i(E^i)^2 \tag{22}$$

where

$$\alpha^i=q^iB^i_m$$

$$\beta^i=(q^i)^2/a^i.$$

1. Optimal Sustainable Yield (OSY)

Economic optimality in the chosen stationary state (OSY) requires maximization of the stationary profit of the multiple species fishing industry:

$$\sum^i p^i\{\alpha^iE^i-\beta^i(E^i)^2\}-wE^i. \tag{23}$$

Thus, the necessary condition for OSY is that the fishery resources should be managed at levels where the fisheries of individual species just break even at

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(7) This specification of fishery population dynamics, often alternatively referred to as the "Schaefer type" fishery model, is commonly attributed to Schaefer 〔15〕 and Gordon 〔7〕

(8) For discussions of stationary fishery of single species, see Gordon 〔7〕, Gulland 〔8〕, Bell 〔2〕, Cadima〔3〕, and Kim 〔12〕, etc.

the margin in the stationary state context, i.e., where marginal sustainable revenue equals marginal cost:

$$p^i(\alpha^i-2\beta^iE^i)-w=0 \qquad i=1,2,\dots,n. \qquad (24)$$

2. Maximum Sustainable Yield (MSY)

Alternatively, biological optimality in the stationary state context (MSY) requires that the stationary catch (revenue) be maximized. Thus, under the MSY, species should be managed at levels where the marginal sustainable catch (revenue) is equalized to zero for all the species involved:

$$p^i(\alpha^i-2\beta^iE^i)=0 \qquad i=1,2,\dots,n. \qquad (25)$$

The MSY fishery regime would be equivalent to the OSY fishery regime if harvesting were costless.

3. Uniform Profitability (UPY)

For the individual fisherman (as represented by the fisherman j), who has to allocate his given endowment of production factors (fishing effort) to the fishing of multiple species, the profit maximization is equivalent to maximization of the Lagrangean:

$$L=\sum^{i}\left(p^i\frac{C^i}{E^i}E^i{}_j-wE^i{}_j\right)+\lambda\left(\bar{E}_j-\sum^{i}E^i{}_j\right).$$

As shown in the previous section, the condition for a private optimum is that the average sustainable revenue (and average sustainable profit) must be equalized across the fishing industry:

$$p^i\frac{C^i}{E^i}=\text{constant}(=w+\lambda) \qquad i=1,2,\dots,n$$

i.e.,

$$p^i(\alpha^i-\beta^iE^i)=p^h(\alpha^h-\beta^hE^h) \qquad i\neq h. \qquad (26)$$

Unless the average sustainable revenue is uniform among alternative species fisheries, there will be intra-firm movements of fishing effort (disequilibrium): The above condition is necessary to maintain private economic equilibrium.

4. Open Access (BEY)

Examination of the above condition (26) further reveals that sustained fishery operation under the competitive condition converges to the state of exploitation where the production factor endowment is not a binding constraint for the fishery industry as a whole. Thus, unrestricted competition induces overfishing to the extent that any potentially existing economic rent is completely dissipated in the long run. This state of fishery is commonly called the bionomic equilibrium (BEY), and the fishery at BEY can be characterized by the equality of average sustainable profit to zero over all the species:

$$p^i(\alpha^i-\beta^i E^i)-w=0 \qquad i=1,2,\ldots,n. \tag{27}$$

If the fishery management authority is required to guarantee uniform profitability, the managing rule would be maximization of stationary rent from fishing subject to the private equilibrium condition (UPY). This is equivalent to maximization of the Lagrangean:

$$L=\sum^{i}[p^i\{\alpha^i E^i-\beta^i(E^i)^2\}-wE^i]+\sum_{h=2}^{n}\psi^h\{p^1(\alpha^1-\beta^1E^1)-p^h(\alpha^h-\beta^hE^h)\}. \tag{28}$$

The necessary condition for UPY is:

$$L^1{}_E=p^1(\alpha^1-2\beta^1E^1)-w-\sum^{h}\psi^h p^1\beta^1=0$$

for the species 1, and

$$L^h{}_E=p^h(\alpha^h-2\beta^hE^h)-w+\psi^h p^h\beta^h=0$$

for the species h $(h=2,3,\ldots,n)$ which can be summarized as

$$\sum^{i}\frac{p^i(\alpha^i-2\beta^iE^i)-w}{p^i\beta^i}=0. \tag{29}$$

This, together with the equilibrium condition (26), constitutes the full set of necessary condition for the UPY fishery regime. Interpretations are similar to what has been discussed in the previous section for condition (18).

With a simple case where only two species are involved in a fishery from a common fishing ground, Figure 1 explains alternative fishery regimes so far discussed in the stationary state context.(9)

In Figure 1, the revenue-effort relationships are drawn on parabolic curves and the cost-effort relationship is drawn with a straight line, reflecting the

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(9) From here on, the word "sustainable" will be excluded from the text unless its use is necessary for clarification.

stationary state specification of the "surplus producton" model and the assumption of constant unit cost of fishing effort. On the basis of what has been discussed, OSY fishery regime is shown to induce fishing efforts E^1_0 and E^2_0, where marginal revenue (the slope of the revenue curve) equals marginal cost (the slope of the cost line). In this case, marginal profit is equalized at zero for all species individually, while average profit is not equalized across the fishing industry.

On the other hand, UPY would result in fishing efforts such as E^1_+ and E^2_+, where marginal revenue (in general) does not equal marginal cost: Marginal profit is not equalized across the fishing industry. Under the UPY fishery regime, however, average profit, by definition, is equalized among different species (in general at a non-zero level). The diagram shows that the constraint of private economic equilibrium transforms the OSY in such a way that

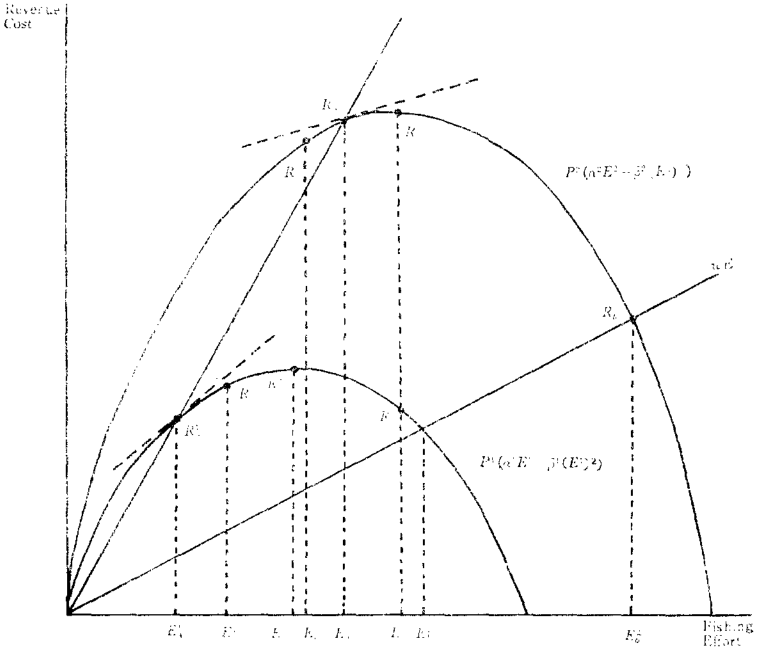

Fig. 1. Multiple Species Fishery Regimes

marginal profit is positive for some species (species 1) while the opposite is true for others (species 2). This, in turn, implies that the UPY fishery regime renders such a state of exploitation that some (species 1) are exploited less and others (species 2) are exploited beyond the levels expected under the OSY fishery regime.

Additionally shown in Figure 1 are the fishery regimes corresponding to MSY and BEY. In the diagram, the MSY fishery regime is expected to result in fishing efforts E^1_m and E^2_m while the BEY fishery regime would induce fishing efforts E^1_b and E^2_b. In the following sections, efficiency aspects of the four alternative fishery regimes—OSY, UPY, MSY and BEY—are examined empirically.

IV. Application

Among major fisheries, the North Sea fishery offers a prime testing ground for the empirical model proposed in this paper. As a first step toward empirical investigation of the efficiency aspects in fishery management, the locus of the sustainable catch-effort relationship (22) is estimated for individual demersal species. This is followed by construction of the cost function, wE, which then allows quantification of potential rent under alternative fishery management regimes.

Due to the well-known paucity of appropriate economic data on fisheries, there have been few successful attempts at empirical applications for the "surplus production" model discussed here. The model assumes that the fishery is restricted to a single fishing ground. The present study, by and large, accomodates this assumption, since it chooses a relatively large fishing ground, the North Sea, and its scope is confined to demersal species whose migratory patterns are more narrowly restricted than those of other species.(10) In addition,

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(10) Demersal species are bottom-dwelling species, distinguished from pelagic species whose migratory patterns are not confined to a single fishing ground. The demersal species chosen for individual investigations are cod, haddock, plaice, saithe, and whiting; others are aggregated into "miscellaneous species" category.

the model assumes that fishery technologies are directive toward single species and that species are biologically independent whereas in reality biological and technological conditions mandate a mixed-species approach.

The empirical specification offered here starts by weighting the catch of individual species by its relative price to a numeraire species (here, the cod price is employed as the numeraire, whose unit is called value-weighted cod equivalent weight, CEW, in short). Thus, the value-weighted catch of species i, R^i, is:

$$R^i = C^i p^i$$

where C^i is the catch weight and p^i is the price of species i relative to that of cod.

In the "surplus production" fishery model, fishing is envisioned as being carried out with a single composite factor of production, the fishing effort. Following other studies, this study measures fishing effort in terms of fishing hours of a "standard fishing boat."(11) Thus, the effective fishing effort directed toward individual species in the total fishery from the North Sea (R^i) is estimated by

$$E^i = R^i / \left(\frac{\sum^i R^i{}_s}{h_s} \right.$$

where $R^i{}_s$ is the value-weighted catch of species i and h_s is the total fishing hours of the standard boat.(12)

It is assumed that the fishing power of boats changes in direct proportion to the change in boat tonnage. Since the tonnage characteristics of the standard boat (the British motor trawlers) have remained roughly constant over time, this assumption implies that the productivity of the standard boat is assumed to have remained constant over the sample period.(13)

Finally this study is restricted to annual observations for the period from

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(11) This procedure can be justified on the basis of private economic equilibrium condition that in each fishing period the average revenue should be equalized across fishery industry.

(12) See the appendix for definitions and underlying assumptions in constructing fishing effort data in terms of the effective unit of the standard boat.

(13) As shown in Kim [12], relaxation of this assumption does not change qualitative conclusions.

Table 1. Demersal Species Fisheries from the North Sea
(Catch)

Year	Cod	Haddock	Plaice	Saithe	Whiting	Others
1954	80. 571	70. 135	66. 965	33. 300	64. 815	133. 347
1955	83. 448	87. 656	63. 315	40. 892	72. 436	168. 828
1956	80. 267	93. 917	63. 881	46. 598	74. 943	219. 976
1957	94. 981	105. 304	69. 272	51. 850	84. 314	264. 370
1958	103. 733	96. 191	72. 429	47. 772	77. 484	283. 065
1959	109. 467	79. 670	78. 324	46. 655	80. 491	387. 001
1960	104. 399	66. 424	86. 289	28. 959	53. 123	328. 793
1961	105. 811	67. 238	85. 783	31. 010	83. 289	287. 590
1962	89. 558	52. 419	87. 419	22. 276	68. 967	459. 008
1963	105. 921	59. 398	107. 062	27. 571	98. 653	583. 420
1964	121. 550	198. 706	110. 361	55. 102	99. 528	474. 947
1965	179. 469	221. 700	96. 927	68. 907	106. 694	452. 071
1966	219. 702	268. 958	100. 130	86. 927	155. 153	431. 402
1967	249. 803	167. 408	100. 646	72. 504	91. 245	574. 258
1968	285. 314	139. 469	108. 838	97. 397	144. 920	854. 301
1969	199. 035	639. 175	121. 652	105. 980	199. 029	460. 348
1970	224. 742	671. 831	130. 344	169. 507	181. 506	688. 223
1971	320. 031	257. 915	113. 921	206. 274	112. 239	949. 934
1972	346. 311	213. 247	123. 150	198. 621	108. 774	1024. 869
1973	235. 502	195. 779	130. 214	182. 356	142. 935	909. 857

(Estimated Fishing Effort)

Year	Cod	Haddock	Plaice	Saithe	Whiting	Others
1954	155. 744	178. 954	319. 725	48. 276	111. 506	440. 770
1955	137. 978	185. 518	266. 958	47. 329	93. 421	496. 890
1956	138. 265	207. 076	302. 608	60. 201	107. 148	693. 429
1957	193. 736	247. 011	315. 091	68. 744	116. 945	830. 437
1958	217. 565	242. 097	329. 644	68. 132	113. 758	914. 281
1959	254. 226	236. 832	387. 445	70. 428	142. 068	1429. 040
1960	287. 950	207. 025	490. 278	48. 722	111. 357	1333. 090
1961	318. 593	232. 819	529. 493	65. 358	180. 561	1333. 520
1962	269. 997	194. 379	582. 442	49. 696	155. 940	2463. 170
1963	389. 015	281. 414	711. 702	58. 730	221. 016	3321. 220
1964	405. 518	762. 367	640. 649	86. 401	167. 947	2456. 020
1965	549. 036	752. 836	554. 495	99. 077	153. 409	2323. 420
1966	623. 021	861. 849	559. 370	118. 322	250. 786	2030. 760
1967	711. 264	624. 426	512. 959	103. 220	177. 014	2763. 290
1968	807. 157	505. 037	615. 809	143. 280	315. 685	4785. 320
1969	524. 854	2191. 150	583. 847	131. 350	404. 125	2500. 700
1970	668. 219	2377. 070	592. 948	226. 796	329. 187	3478. 660
1971	986. 167	977. 553	431. 808	286. 033	183. 307	3424. 820
1972	1229. 490	908. 497	524. 657	303. 226	235. 567	4257. 060
1973	1116. 860	1030. 610	685. 467	337. 280	345. 712	4401. 280

Source: *Bulletin Statistique*, ICES, various issues.

Units: Catch in 1 ton and effort in 1 fishing hour.

1954 to 1973. During this period, unlike at present, quotas were not imposed and fishing took place in an open-access environment.(14) Table 1 summarizes the data on catch and effort for individual species during the sample period.

V. Results

1. Sustainable Revenue-Effort Regressions

Due to biological factors—most notably, age composition and reproduction characteristics—current fishing influences not only current but also future harvest potentials. However, this relationship is not known with accuracy. Lacking any prior knowledge of these intertemporal effects, four alternative regressions of the sustainable revenue-effort relationships (31) are offered here: Two regressions by the ordinary least estimation, and other two regressions by the Cocrane-Orcutt estimation.

These regressions differ only by the lag structure imposed on the independent variables, with the general regression equation being:

$$R^i=\alpha^i\bar{E}^i-\beta^i(\bar{E}^i)^2 \tag{31}$$

where

$$\bar{E}^i=\sum_{t=0}^{s}E^i{}_{t-s}/(s+1)$$

The two regressions differ according to s being alternatively set at 0 and 3. Individual results are reported in Tables A2 and A3 in the appendix, and their summary are presented in Table 2.

The unit (harvesting) cost of fishing effort has been calculated at 210.9 CEW tons per 1000 fishing hours. (For derivation of harvesting cost, see the appendix.)(15)

Summary estimates show the average slope of the following regression results

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(14) While quotas were not imposed during the sample period, technological restrictions, however, are widely considered as not having led to sizable impact on overfishing. Cf. ICES [11], Saedersdal [14], or the "Review of State" series of FAO [6].

(15) Under higher cost assumption, the unit cost of fishing effort is estimated at 288.2 CEW tons per 1000 fishing hours.

Table 2. Summary Estimates of Catch-Effort Regressions: $C=aE+bE^2$

Species	a	b
Cod	498. 6	−. 2080
Haddock	623. 4	−. 2248
Plaice	603. 0	−. 5062
Saithe	488. 0	−. 7160
Whiting	495. 0	−. 6002
Others	508. 4	−. 0552

reported in Tables A2 and A3:

Species	*Equation Numbers*
Cod	1-1, 1′-1, 1′-2
Haddock	2′-1
Plaice	3-1, 3-2 3′-1
Saithe	4-1, 4-2, 4′-1
Whiting	5′-1
Others	6-1, 6′-1, 6′-2

Choice of equations is based on the significance and the sign of estimated coefficients. The coefficients of chosen regression results are all significant at 2% level, except those of the catch-effort regression of whiting.

2. Efficiency Aspects

In this section, with the measurement of fishing effort, revenue, cost, and profit, the efficiency consequences of the four alternative regimes will be examined. Table 3 shows the estimation results for the aggregate case of the entire North Sea fishery as well as for individual demersal species fisheries.(16)

(1) The Economic Optimum (OSY) Regime

Under the economic optimum regime, whose optimality criterion is the maximum flow of economic rent from fishing, the demersal species fisheries of the North Sea taken as a whole are expected to yield 1. 91 million CEW tons of

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(16) The resuts in this section pertain to the cases under tlhe low cost assumption. For the results under the high cost assumption, see table A4 in the appendix.

revenue at a harvesting cost of 1.08 million CEW tons. Total fishing effort amounts to 5.12 million hours. The aggregate profit is 826 thousand CEW tons and the average profit rate is 76.5%.

Of the five individual demersal species fisheries of the North Sea, the haddock fishery is shown to have the largest potential revenue of 383 thousand CEW tons while the saithe fishery has the smallest potential revenue expected at 68 thousand CEW tons. The haddock fishery also has the largest total har-

Table 3. North Sea Demersal Fisheries under Alternative Regimes

	Aggregate	Cod	Haddock	Plaice	Saithe	Whiting	Others
1 Effort							
OSY	5121.4	691.6	917.5	387.3	193.5	236.7	2694.8
UPY	5121.3	623.5	1132.1	462.4	166.3	210.1	2526.9
MSY	8539.1	1198.6	1386.6	595.6	340.8	412.4	4605.1
BEY	10242.5	1383.1	1835.0	774.6	387.0	473.3	5389.5
2 Revenue							
OSY	1905.9	245.3	382.7	157.6	67.6	83.5	969.2
UPY	1889.3	230.0	417.6	170.6	61.4	77.5	932.2
MSY	2266.5	298.8	432.2	179.6	83.2	102.1	1170.6
BEY	2160.1	291.7	387.0	163.4	81.6	99.8	1136.6
3 Cost							
OSY	1080.1	145.9	193.5	81.7	40.8	49.9	568.3
UPY	1081.1	131.5	238.8	97.5	35.1	44.3	532.9
MSY	1800.9	252.8	292.4	125.6	71.9	87.0	971.2
BEY	2160.1	291.7	387.0	163.4	81.6	99.8	1136.6
4 Profit							
OSY	825.9	99.5	189.2	75.9	26.8	33.6	400.9
UPY	809.2	98.5	178.9	73.1	26.3	33.2	399.3
MSY	465.6	46.0	139.8	54.0	11.3	15.1	199.4
BEY	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 Profit Rate							
OSY	76.5	68.2	97.8	93.0	65.7	67.4	70.5
UPY	74.9	74.9	74.9	74.9	74.9	74.9	74.9
MSY	25.9	18.2	47.8	43.0	15.7	17.4	20.5
BEY	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Table 2 and the low cost assumption of 210.9 CEW tons per 1000 fishing hours.

Units: Effort in 1000 hours; revenue in 1000 CEW tons; cost in 1000 CEW tons; profit in 1000 CEW tons; and profit rate in per centage.

vesting cost at 194 thousand CEW tons, and the saithe fishery the lowest at 41 thousand CEW tons.

In terms of the optimum potential economic rent, the haddock fishery is the most promising with 189 thousand CEW tons and the saithe fishery ranks last with only 27 thousand CEW tons. The average profit varies from 66% for the saithe fishery to 98% for the haddock fishery.

(2) The Uniform Profitability (UPY) Regime

Under the management constraint of uniform profitability, where the flow of economic rent is maximized while maintaining an equal profit rate across the entire fishing industry, the aggregate demersal species fishery of the North Sea is expected to yield 809 thousand CEW tons as the economic rent; the aggregate revenue is 1. 89 million CEW tons at a harvesting cost of 1. 08 million CEW tons, and the total fishing effort amounts to 5. 12 million hours. The fishery profit is therefore equivalent to 74. 9% of harvesting cost, which is uniformly applicable for all the fisheries of the individual species.

Among the individual species, the largest total revenue of 418 thousand CEW tons is obtained for the haddock fishery while the smallest revenue of 61 thousand CEW tons is expected for the saithe fishery. Correspondingly, the haddock fishery requires the highest total harvesting cost at 239 thousand CEW tons and the saithe fishery has the lowest cost at 35 thousand CEW tons. As a result, the largest economic rent is expected from the haddock fishery at 179 thousand CEW tons, whereas the smallest rent is expected from the saithe fishery at 26 thousand CEW tons.

(3) The Biological Optimum (MSY) Regime

Under the biological optimum regime, whose optimality requires maximization of the flow of fishery catch irrespective of harvesting cost, aggregate rent amounts to 466 thousand CEW tons. Aggregate revenue is about 2. 27 million CEW tons and the corresponding aggregate harvesting cost is 1. 80 million CEW tons. The aggregate average profit is around 26%.

In terms of the relative magnitude of the results for individual species, the same observations as before can be made. Thus, under the MSY regime, the haddock fishery would generate the largest revenue of 432 thousand CEW tons, and the saithe fishery would yield the smallest revenue of 83 thousand CEW tons. The corresponding harvesting cost for the haddock fishery is 292 thousand CEW tons, and that for the saithe fishery is 72 thousand CEW tons.

It should be emphasized here that under the MSY regime the potential economic rent is quite small while the revenue is large. This follows from the neglect of harvesting cost. The largest fishery profit under the MSY regime (from the haddock fishery) would amount to only 140 thousand CEW tons, while the smallest profit (from the saithe fishery) would be minimal 11 thousand CEW tons. Consequently, the average profit rates for the individual species fisheries under the MSY regime range from 16% to 48%, revealing not only low levels but also wide differences in profitability among species.(17)

(4) The Open Access (BEY) Regime

Finally, Table 3 also reports the results for the open access regime, which is characterized by the lack of an active fishery management and, thus, by the complete dissipation of economic rent. Here again, the largest fishery activity is shown for the haddock fishery, and the opposite is true for the saithe fishery. Under open access, the fishery in the aggregate will generate 2.16 million CEW tons at an effort of 10.2 million fishing hours.

VI. Conclusion

This study has investigated the demersal species fisheries of the North Sea within the stationary state context of the "surplus production" fishery model. The empirical findings show that fishery policies following the biological optimum (MSY) or the open access (BEY) criteria would forego economic rents in

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(17) As can be seen in table A4 in the appendix, the average profit of individual species fisheries under the MSY regime would range between −15% and 8% under the alternative high cost assumption.

the amounts of 360 and 826 thousand CEW tons, respectively, as compared with the economically first-best regime (OSY). The large welfare losses implied by open access, i.e., lack of any active fishery policy, may not come as a surprise. What is surprising, however, is that biological optimality (MSY) is revealed as an inappropriate management criterion.

In contrast, the uniform profitability (UPY) regime fairs quite well in comparison with the first-best choice of the OSY regime. The efficiency loss of the UPY regime—as measured by the difference in the potential economic rent—amounts to only 17 thousand CEW tons, which is about 2% of the rent under the OSY regime. Though inferior to the OSY regime, the UPY regime, is a very close second-best choice. The most striking difference between these two fishery regimes lies in the interspecies variation of profit rates: Under the OSY regime, the variation is as wide as 32%, while under the UPY regime, by definition, equal profit rates are maintained across the fishing industry. If the management authority might—for distributional reasons—consider it imperative that profit opportunities among the fisheries of individual species in the region should be equalized, it may, as this paper suggests, opt for such a regime without fear of major efficiency losses.

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Appendix(18)

Catch: The value-weighted catch figures of the North Sea demersal species fisheries are derived (i) from absolute catch weight data as reported in *Bulletin Statistique* by the International Council for the Exploration of the Sea (ICES), various issues, and (ii) on the basis of relative catch prices of British takings as reported in *Sea Fisheries Statistical Tables,* various issues, by the Ministry of Agriculture, Fisheries and Food, U.K.

Fishing Effort and Catch Per Unit of Fishing Effort: This study follows the common practice of relying on a composite factor of production, fishing effort. Fishing effort is

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(18) The data construction is based on Kim [12]. It is repeated here for convenience.

measured by fishing hours of the "standard boat," British motor trawlers, as reported in ***Bulletin Statistique***. This procedure is based on the assumption that all the fishing boats are subject to the same condition (as represented by the catch per unit of fishing effort) as that experienced by the standard boat on the common fishing ground. This has been formally proved with the private economic equilibrium condition (10). Catch per unit of effort (CPUE) is obtained by dividing the value-weighted catch by fishing hours of the standard boat as reported in Table A1.

Unit Cost of Fishing Effort: Direct cost data on the multiple species fishery of the North Sea are not available. To obtain proxies for the unobserved cost data, this study invokes the open access equilibrium condition that in the long run, revenue must be at least as high as harvesting cost. Thus, the observed CPUE should be at least as high as the un-

Table A1. England & Wales Fishing Efforts and Catches with (Bottom) Motor Trawlers

Year	Effort		Catch						Total Weight	Total Cod-valued Weight
	Fishing Hour	Average Gross Tonnage	Cod	Haddock	Plaice	Saithe	Whiting	Others		
1954	8, 524	—	178	105	—	926	7	1, 984	3, 200	4, 410
1955	13, 959	—	480	350	4	2, 536	8	3, 215	6, 593	8, 842
1956	10, 949	357	330	330	4	2, 509	13	2, 022	5, 208	6, 356
1957	13, 220	359	473	544	9	2, 550	36	2, 390	6, 002	6, 481
1958	19, 076	--	746	1, 103	21	3, 422	76	2, 987	8, 355	9, 095
1959	32, 929	—	1, 488	1, 477	23	4, 859	49	4, 752	12, 648	14, 179
1960	32, 192	—	1, 106	1, 032	18	4, 003	19	4, 698	10, 876	11, 672
1961	40, 699	—	1, 405	729	20	4, 029	17	5, 455	11, 655	13, 517
1962	40, 301	353	1, 713	1, 179	46	3, 303	51	4, 284	10, 572	13, 368
1963	40, 578	324	1, 538	1, 093	255	3, 759	81	3, 490	10, 216	11, 049
1964	44, 774	330	2, 551	1, 633	399	3, 990	37	4, 130	12, 740	13, 420
1965	40, 969	339	1, 936	1, 484	426	5, 287	51	3, 871	13, 055	13, 392
1966	50, 892	341	2, 452	4, 131	674	6, 077	154	3, 912	17, 400	17, 946
1967	45, 237	334	2, 741	3, 213	924	5, 001	100	2, 790	14, 769	15, 888
1968	68, 379	321	6, 287	3, 056	2, 427	3, 603	66	3, 633	19, 072	24, 170
1969	46, 257	343	4, 358	2, 365	1, 202	3, 644	78	2, 985	14, 623	17, 542
1970	34, 791	308	2, 489	2, 385	1, 280	2, 428	55	1, 935	10, 572	11, 701
1971	73, 431	291	7, 018	5, 944	3, 827	2, 873	88	2, 952	22, 702	23, 830
1972	107, 271	342	9, 709	6, 508	5, 155	3, 265	170	4, 276	29, 083	30, 215
1973	88, 365	347	5, 004	2, 811	5, 887	2, 748	116	2, 787	19, 353	18, 632

Source: ***Bulletin Statistique***, ICES.
Units: Effort in 1 fishing hour and catch in 1 ton.

observed unit cost of effort; and consequently, following Hannesson [9] and as utilized in Kim [12], the unit cost can be inferred by the lowest historical level of CPUE. For the North Sea fisheries considerd here, 1973 shows the lowest CPUE level, which is employed as the low unit cost of fishing effort. For the high cost calculation, the *minimum* of four year averages of CPUE over the observation period (1954～1973) is employed. This turns out to be the average of the years 1970～1973. This alternative cost figure is offered on the presumption that the low 1973 CPUE *may* reflect short-run disequilibrium phenomena.

Table A2. Catch-Effort Regressions: $C=\alpha E+\beta E^2$

Species	Equation Number	α	β	Standard Error of Regression	D-W	P
Cod	1-1	429.9(13.69)	−.1391 (4.10)	27.5	.99	
	1-2	239.1 (2.21)	.0252 (.33)	23.7	.60	.91
Haddock	2-1	305.4(10.62)	.0196 (1.29)	44.3	.70	
	2-2	302.8 (5.91)	.0187 (.96)	36.7	1.87	.71
Plaice	3-1	675.5(13.50)	−.6017 (6.86)	22.1	.75	
	3-2	440.2 (3.73)	−.2736 (2.14)	15.2	1.51	.89
Saithe	4-1	453.0(15.15)	−.6062 (5.39)	7.0	.62	
	4-2	489.3 (7.51)	−.7598 (3.72)	5.3	1.05	.73
Whiting	5-1	399.2 (7.70)	−.2255 (1.27)	16.2	.50	
	5-2	148.8 (1.26)	.3363 (1.40)	10.0	1.26	.91
Others	6-1	411.5 (9.66)	−.0277 (2.38)	141.5	.85	
	6-2	258.2 (2.49)	.0051 (.31)	110.3	1.06	.89

Notes: (1) The regression is done with the current fishing effort as the independent variable.
(2) Units of the catch and the fishing effort are CEW tons and 1,000 fishing hours, respectively. The unit for the standard error of regression is 1,000 CEW tons.
(3) The regression results numbered with "-1" are the results of ordinary least squares estimation, and those numbered "-2" are the results Cochrane-Orcutt estimation.
(4) The numbers in parentheses are t-statistics.

Table A3. Catch-Effort Regressions: $C=\alpha'\cdot PE+\beta\cdot.PE^2$

Species	Equation Number	α'	β'	Standard Error of Regression	D-W	P
Cod	1′-1	523.8 (8.98)	−.2266 (2.88)	38.1	1.53	
	1′-2	542.1 (7.28)	−.2584 (2.65)	38.5	1.61	.23
Haddock	2′-1	623.4 (3.48)	−.2248 (1.67)	173.5	1.29	
	2′-2	622.0 (2.50)	−.2256 (1.24)	170.1	1.59	.34
Plaice	3′-1	693.4 (9.15)	−.6433 (4.69)	23.7	.78	
	3′-2	551.1 (2.99)	−.4132 (1.31)	19.8	1.81	.71

Saithe	4′-1	521.7(10.39)	−.7820 (3.31)	10.1	.92	
	4′-2	155.0 (4.82)	−.3410 (4.78)	7.1	1.97	1.04
Whiting	5′-1	495.0 (4.54)	−.6002 (1.38)	24.1	1.14	
	5′-2	436.4 (2.45)	−.3758 (.55)	22.4	1.70	.43
Others	6′-1	560.6 (6.07)	−.0701 (2.34)	216.8	1.88	
	6′-2	553.0 (5.53)	−.0678 (2.10)	223.0	1.94	.03

Notes: (1) The regression is done with the average fishing effort of the current and past three years as the independent variable.
(2) Units are as explained in Table A2.

Table A4. North Sea Demersal Fisheries under Alternative Regimes: High Cost Assumption

	Aggregate	Cod	Haddock	Plaice	Saithe	Whiting	Others
1 Effort							
OSY	3,868.7	505.8	745.6	310.9	139.5	172.3	1,994.6
UPY	3,868.6	437.7	960.1	386.1	112.3	145.7	1,826.7
MSY	8,539.1	1,198.6	1,386.6	595.5	340.8	412.7	4,605.1
BEY	7,737.3	1,011.5	1,491.1	621.7	279.1	344.6	3,989.1
2 Revenue							
OSY	1,593.4	199.0	339.8	138.6	54.1	67.5	794.4
UPY	1,576.7	178.4	391.3	157.4	45.8	59.4	744.5
MSY	2,266.5	298.8	432.2	179.6	83.2	102.1	1,170.6
BEY	2,230.1	291.5	429.7	179.2	80.4	99.3	1,150.0
3 Cost							
OSY	1,114.9	145.8	214.9	89.6	40.2	49.6	574.8
UPY	1,114.9	126.1	276.7	111.3	32.4	42.0	526.5
MSY	2,460.9	345.4	399.6	171.7	98.2	118.8	1,327.2
BEY	2,230.1	291.5	429.7	179.2	80.4	99.3	1,150.0
4 Profit							
OSY	478.4	53.2	125.0	48.7	13.9	17.8	219.6
UPY	461.8	52.2	114.6	46.1	13.4	17.4	461.4
MSY	−194.6	−46.6	32.6	7.9	−15.1	−16.8	−156.6
BEY	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 Profit Rate							
OSY	42.9	36.5	58.1	54.6	34.7	35.9	38.2
UPY	41.4	41.4	41.4	41.4	41.4	41.4	41.4
MSY	−7.9	−13.5	8.2	4.6	−15.3	−14.1	−11.8
BEY	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source and units: The same as in Table 3; calculations are based on the high cost assumption of 288.2 CEW tons per 1,000 fishing hours.