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Measuring Potential Rents in the North Sea Herring Fishery

ABSTRACT. *This paper assesses the potential for rent generation in the North Sea herring fishery. The assessment distinguishes between rents and intra-marginal profits the sum of which constitutes variable profits in the fishery. A bioeconomic model combining fish population dynamics and the economics of the fishery is constructed to allow the computation of these different components of profits. In order to assess the dynamics of both rents and intra-marginal profits, the model is computed under various assumptions with regard to price, costs, and discount rates. Potential total profits are measured at £88-89 million annually of which rents makes up about £87 million with intra-marginal profits measured in the order of only £2 million. The study further shows that, in this fishery, rent is dissipated mainly due to excess effort but also due to suboptimal stock size.*

(JEL Q22, Q28)

Short Title: Rents in the North Sea Herring Fishery
Keywords: North Sea Herring, Bioeconomic model, Rents, Intra-marginal Profits

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I. INTRODUCTION

The great majority of marine fisheries around the world are characterised by very poor economic returns as well as stock overexploitation (World Bank and FAO 2009; FAO 2016). In the fisheries economic literature, the concept of economic rents has been traditionally used as a key indicator of economic performance (Gordon 1954; Anderson 1977, Hannesson 1993, Coglan and Pascoe 1999; Homans and Wilen 2005; World Bank and FAO 2009). Following this terminology, the distressed state of the global fishery has often been described as foregone economic rents or rent loss (World Bank and FAO 2009). Dissipation of economic rents in fisheries is due to mismanagement of the resource resulting in stock depletion and/or excess fishing capacity (e.g. Bjørndal and Munro 2012).

Maximum rent in fisheries is obtained by following the appropriate fishing effort, or, equivalently, harvesting path over time. In most existing fisheries this policy would, in the long run, converge to a fishery equilibrium with a large sustainable biomass and high annual rents (see e.g. Clark 1990).[1] Efficient fisheries management is required to achieve this favourable outcome. Conversely, without some degree of effective fisheries management, the shared nature of fish resources leads to a severe, even complete, dissipation of attainable rents (Gordon 1954; Clark 1990, Homans and Wilen 2005). As pointed out by Copes (1972) and others[2], the commonly held notion that open access fisheries yield no rents is not accurate. It ignores the fact that profits may be earned by

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[1] For completeness, it should be mentioned that in certain, very special cases, maximising rents may not lead to a sustainable fishery (Clark 1990).

[2] See also Geen and Nayar 1988; Johnson and Libecap 1982, Nugeyen *et al.* (2012) and Coglan and Pascoe 1999.

intra-marginal units employed in the fishery. This fact further suggests that total variable profits in fisheries should generally be seen as the sum of economic rents and intra-marginal profits.

The purpose of this paper is to assess profits, rents and intra-marginal profits in the North Sea herring fishery under current as well as optimal management. Data for the UK pelagic trawl fleet are used to approximate the profit structure for an average vessel fishing herring in the North Sea. Our empirical strategy follows Arnason (2011), who estimates a global fishery model and obtains estimates of the rent loss in the world's capture fisheries. *The Sunken Billions* report (World Bank and FAO, 2009) estimates potential economic rents from world fisheries of $45 billion per year (2004 price level) under optimal management compared to actual rents of approximately -$5 billion. This implies that globally attainable fisheries rents are depleted due to overexploitation of stocks and excessive application of fishing effort. The situation calls for major investmentS in fish stocks and disinvestment in fishing capital in the fisheries of the world (Bjørndal and Munro, 2012).

A major contribution of the paper is the differentiation between rents and intra-marginal profits, which serves to clarify considerable confusion in the fisheries economics literature regarding both the definition and the sources of these two types of profits (Arnason, 2008). The conceptual analysis employs a theoretical framework that formulates the sources and evolution of the two types of profits and how they are associated with competitive and profit maximising equilibria. Based on this, a dynamic optimisation model is built to empirically estimate rents and intra-marginal profits under alternative management scenarios. Such assessment of the two types of fisheries profits in a unified framework constitutes, as far as we have been able to verify, a new approach in the empirical fisheries literature.

The paper is organised as follows. Section II defines resource rent and intra-marginal profits and provides a review of the relevant theory on rents in fisheries. This is followed, in Section III, by an overview of the North Sea herring fishery and a description of UK fleet and vessel statistics including an evaluation of current economic profits in the fishery. A bioeconomic model, consisting of a model of population dynamics and fisheries profits, is formulated in Section IV and conditions for a dynamic optimum are derived. Estimation, calibration and simulation results of the dynamic optimisation are reported in Section V. Concluding comments are offered in the final section.

II. PROFITS, RENTS AND INTRA-MARGINAL PROFITS

The concept of rents in fisheries derives from the more general concept of economic rents which was discussed in Smith (1776) and further developed by Ricardo (1821). In modern usage, economic rents are defined as payments to a factor of production over and above what is needed to obtain its use (Robinson 1939; Alchian 2008). This may occur as a consequence of fixed supply of the factor (Alchian 2008). When the factor of production is a natural resource, economic rents are often referred to as resource rents (Copes 1972, Anderson 1977, Cooke and Copes 1987, Hannesson 1993, Arnason 2011). This terminology, however, should not be interpreted to suggest that these rents arise from the natural resource only. In fisheries as well as other natural resource use, various other factors of production including technology are invariably involved in generating these rents.

To clarify the concept of rents in the context of the fishery, we employ a standard simple fisheries model (see e.g. Clark and Munro, 1975). Within this model a general fisheries profit function may be written as:

$$\pi = \pi(H, S) \qquad [1]$$

where H denotes the harvest quantity and S the size of the fish stock. This function is assumed to be at least weakly concave in both variables and increasing in S. Moreover, $\pi(0,S) \leq 0$, i.e., there may be costs associated with being in the fishery even if harvest is zero. In what follows, we will assume that this profit function is at least twice continuously differentiable.

The fish stock is taken to evolve in the usual way as:

$$\dot{S} = G(S) - H\,, \qquad [2]$$

where $\dot{S} \equiv \frac{dS}{dt}$ is the instantaneous change in stock size and the function $G(S)$ is the stock renewal function which is assumed to have the usual dome shaped properties (Clark and Munro 1975). Fish stock equilibrium occurs when $\dot{S}=0$. Thus, in equilibrium the rate of harvest is a function only of the biomass which we then write as $H(S)$.

Competitive or common property equilibrium (where effective fisheries management is not in place) is defined by the two conditions:

$$\pi_H(H°, S°) \equiv \frac{\partial \pi(H°, S°)}{\partial H} = 0\,,\ H°=G(S°), \qquad [3]$$

which yields an equilibrium solution for both biomass, $S°$, and the harvest level, $H°$. Note that in (3), the traditional competitive equilibrium requirement (Gordon 1954) that profits are zero, $\pi(H°,S°)=0$, has been replaced by the condition that marginal profits are zero. It is useful to note that this equilibrium solution does not imply zero variable profits unless the profit function is linear in harvests, *H*. As will be shown below, if the profit function is strictly concave and positive over a range of harvests, there will be positive intra-marginal profits associated with the same range of harvests. This implies positive variable profits.[3] If these are sufficiently large to cover the fixed costs, $\pi(0,S°)$, total profits will also be positive. [4]

The profit maximising equilibrium, by contrast, is characterised by the following two equations:

$$\pi_H(H^*,S^*)=\lambda,\ H^*=G(S^*), \qquad [4]$$

where $\lambda>0$ is the shadow value of the fish stock reflecting the scarcity of biomass (see e.g. Clark and Munro 1975, Arnason 1993).

Having specified the fishery and the equilibria of particular interest, we are now in a position to consider rents. Following Arnason (2006, 2008, 2011), we define rents and intra-marginal profits in the following way:

$$R(H,S)=\pi_H(H,S)\cdot H \qquad [5]$$

$$IP(H,S)=\tilde{\pi}(H,S)-R(H,S) \qquad [6]$$

where $R(H,S)$ denotes rents, $IP(H,S)$ the intra-marginal profits and $\tilde{\pi}$ variable profits. It is useful to note that according to these definitions, the sum of rents and intra-marginal

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[3] That profits could be positive in open access competitive equilibrium has been pointed out by Copes (1972), Johnson and Libecap (1982) among others.

[4] A simple proof of this rather obvious result is obtained by taking an exact 2nd order Taylor expansion of the profit function around the competitive level $H°$ yielding: $\pi(0,S°)=\pi(H°,S°)+\pi_H(H°,S°)\cdot(0-H°)+\Delta$, where Δ represents second order terms and must be negative by the concavity of the profit function. Since $\pi_H(H°,S°)=0$ in competitive equilibrium, it is immediately found that $\pi(H°,S°)=-\Delta+\pi(0,S°)$, which verifies the statement in the text.

profits equal variable profits.

If the profit function is concave, as was assumed above, important properties of rents and intra-marginal profits can be readily derived. Most importantly, both rents and intra-marginal profits are non-negative. To see this, note that profit maximisation by individual fishermen implies that the derivative $\pi_H(H,S)$ is nonnegative. It follows that so are the rents.[5] Moreover, if the profit function is concave, rents cannot exceed variable profits.[6] Hence, in that case, intra-marginal profits, being the difference between variable profits and rents, are also non-negative. They are zero only in the extreme case where the profit function is linear in harvests. Finally, if the profit function is strictly concave, it is easy to show that maximum profits occur at a higher harvest rate than maximum rents.[7] In this sense maximising rents is more conservative of the resource than maximising profits.

The above definitions or rents and intra-marginal profits may be illustrated with the help of figure 1. Assuming that the profit function is strictly concave in harvest, figure 1 draws the marginal profit function (which is also the industry demand function for harvest) as a downward sloping curve. It is important to note that this curve depends on the prevailing stock size, S, as well as various other factors that affect the profit function. If the stock size is lower, the marginal profit curve will shift toward the origin and vice versa. Constraining the harvest level to the optimal level, H^*, the corresponding rents and

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[5] The case of negative rents caused by the industry being forced to operate at negative marginal profits is interesting but is not pursued here.

[6] This is easily shown by taking a 2nd order Taylor expansion of the profit function around any non-negative harvest level.

[7] Maximising rents with respect to harvest implies $\pi_{HH} \cdot H + \pi_H = 0$. Since for a strictly concave profit function, $\pi_{HH} < 0$, rent maximization occurs at lower harvest level than profit maximisation. Only if $\pi_{HH} = 0$, i.e., the profit function is linear in harvest, will rent maximisation coincide with profit maximisation.

intra-marginal profits are defined by the respective areas illustrated in the diagram. Clearly, constraining harvest at any level less than $H°$ will yield positive rents and intra-marginal profits. If there are no restrictions on harvest, the industry will find an equilibrium at $H°$ where marginal profits are zero and rents therefore zero as well. As the diagram in figure 1 makes clear, at $H°$ intra-marginal profits are very high and the sum of rents and intra-marginal profits higher than at the optimal harvest level. This reflects the fact that unconstrained fishing maximizes instantaneous profits at each point of time given the prevailing size of the fish stock. Unconstrained or competitive fishing, however, is dynamically inefficient. Over time it drives the fish stock down which moves the marginal profit function inward toward the origin. Both total and intramarginal profits are thus reduced over time until a competitive equilibrium is reached where profits are typically small and much smaller than those obtainable in optimal equilibrium.

[Figure 1 here]

Expressions [4] and [5] make it clear that both rents and intra-marginal profits depend on the harvest level, the size of the resource (fish stocks) and the various other variables affecting the profit function. Therefore it is misleading to attribute these two measures to one of these variables only. In particular, the rents are not solely generated by the resource. Some amount of the resource is of course necessary for rents, but it is by no means sufficient and the actual size of the rents depends on many other variables, including the harvest level, prices, the technology in use and the efficiency of the harvesting activity. Thus, attributing these rents to the resource only is misleading and employing the term *resource rents* for the rents we have identified can easily be misunderstood.

Similar qualifications apply to the intra-marginal profits. They are commonly attributed to differential efficiency across production units (Copes 1972; Johnson and Libecap 1982; Johnson 1995). While it is true that this would give rise to a downward sloping aggregate marginal profit function, which is necessary for intra-marginal profits, the size of these intra-marginal profits depends also on the harvest level as well as the size of the fish stock level and the various other variables affecting the profit function. Thus, attributing intra-marginal profits only to differential efficiency of the production units is also misleading.

The definitions of rents and intra-marginal profits in [5] and [6] are general and apply both in disequilibrium and equilibrium states of the fishery. In equilibrium, however, these expressions can be simplified by exploiting the equilibrium relationship between harvest and biomass, *H*(*S*), to yield:

$$\tilde{R}(S) = \pi_H(H(S), S) \cdot H(S) \qquad [7]$$

$$\tilde{I}R(S) = \pi(H(S), S) - \tilde{R}(S), \qquad [8]$$

where the $\tilde{R}$ and $\tilde{I}P$ indicate rents and intra-marginal profits in equilibrium respectively. These equilibrium relationships, although written explicitly as functions of biomass only, are actually complicated functions of the fishery profit function and the biomass growth function as will be evidenced in the empirical analysis to follow. Therefore, without additional specifications of these basic functions, it seems difficult to say much about their shape. However, assuming the following standard forms of the two basic functions the shape of these equilibrium rent and intra-marginal rents functions can be worked out:

$$\pi(H, S) = p \cdot H - c \cdot H^a \cdot S^{-b}, \qquad [9]$$

$$G(S) = \alpha \cdot S - \beta \cdot S^2, \qquad [10]$$

where *p* denotes price, *c* a cost parameter and *a*, *b*, α and β are positive constants. Given these basic functions and reasonable values of the parameters, the rents and intra-marginal profits functions may be illustrated as in figure 2.

[Figure 2 here]

Note that rents are maximised at stock size S' which is larger than the stock size that maximises profits, S*. This is because maximising profits implies more harvests than maximising rents as explained above. Note also that at the competitive equilibrium, defined by zero rents and indicated by $S°$ in figure 2, intra-marginal rents are positive. So total variable profits in competitive equilibrium are positive as previously asserted by Copes (1972), Johnson and Libecap (1982), Coglan and Pascoe 1999 and Nugeyen *et al*. 2012) and also found in our empirical analysis of the UK herring fleet to be presented below. It is noteworthy that for these functional specifications at least intra-marginal profits are monotonically declining with equilibrium stock size. This follows from the concavity of the profit function and is made clear in figure 1.

III. THE NORTH SEA HERRING FISHERY

North Sea autumn-spawning herring (*Clupea harengus L*) consists of three spawning stocks with spawning grounds east of Scotland, east of England and in the English Channel. The three stocks mix on the feeding grounds in the central and northern North Sea, and the International Council for the Exploraton of the Sea (ICES) treats North Sea herring as one stock. Herring become sexually mature at age three and can live as long as 15 years. The herring fishery has a season running from May until September.

After World War II, the stock may have been close to the carrying capacity of the environment due to low fishing pressure. Subsequently, open access to the fishery combined with the adoption of more efficient fishing technologies in the 1960s and 1970s substantially increased fishing pressure. This caused the stock to be driven to near extinction in 1977, when a moratorium was introduced (Bjørndal 1988). Various regulations have been in effect ever since so as to allow for a sustainable fishery (Bjørndal and Lindroos 2004).

Spawning stock biomass (SSB) for the period 1960-2007 is illustrated in figure 3. There have been substantial variations in stock size over this period. In 1960, the SSB stood at 1.85 million tonnes, increasing to almost 2.2 million tonnes in 1963. This year saw the introduction of the power block[8] that led to rapid stock depletion, with the stock falling to a low of 47,000 tonnes in 1977, at which time the moratorium was introduced.[9] The figure shows that the stock recovered reasonably quickly. For the years 1988-90, the SSB averaged around 1.2 million tonnes. In the period 2001-06, the SSB varied in the range 1.3–1.8 million tonnes but it was reduced to 977,000 tonnes in 2007. The Blim[10], the level below which the stock should not be reduced as this would endanger future sustainability, is set at 800,000 tonnes.

[Figure 3 here]

Since the introduction of Exclusive Economic Zones in 1977, the North Sea herring fishery has been jointly managed by Norway and the European Union (EU). A Total Allowable Catch (TAC) is set annually for the sustainable management of the

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[8] A mechanical winch that is used to pull in the seines, allowing for much larger nets and eventually larger vessels.

[9] The schooling behaviour of herring has permitted the development of very effective means of harvesting. With modern fish finding equipment, harvesting can be viable even at very low stock levels.

[10] See Horwood (1999).

stock; Norway receiving a 29% share and the rest to the EU. The sharing is largely based on the zonal attachment of the stock to the Exclusive Economic Zones of Norway and the EU, respectively. Within the EU the TAC is shared according to the principle of relative stability, under which member states receive national quotas in such a way as to ensure the relative stability of the fishing activities of each member state.

Total landings of herring are also graphed in Figure 3. Landings increased from about 700,000 tonnes in 1960 to almost 1.2 million tonnes in 1965, and were maintained at a high level into the 1970s despite a declining stock size. Note that in the years 1968-76, annual catches exceeded the size of the SSB[11]. Landings were reduced to 46,000 tonnes in 1977, when the moratorium was introduced, and stayed at a low level until the fishery was reopened in 1981.[12] Landings in 2006 were recorded at more than 500,000 tonnes, falling to 400,000 tonnes in 2007. In most years, Norway records the highest catch followed by Denmark. The Netherlands and UK are also important participants in the fishery.

Regulations of the fishery vary from country to county. In Norway, vessels are regulated with individual quotas that are not transferable, whereas in Denmark and the Netherlands, individual transferable quotas are used. In the UK, most firms receive quota allocations from the producer organisations to which they belong, while larger companies may receive allocations directly from the government. These quotas are to a certain degree transferable.

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[11] Catches include juvenile herring that are part of the total biomass but not the SSB. For example, in 1974 total landings were about 275,000 tonnes. Total biomass and SSB, at the beginning of the year, were 912,000 and 162,000 tonnes, respectively. By the time the fishing season started, both total biomass and SSB would have grown. Thus, the harvest of 275,000 tonnes would be from a larger stock, and a substantial part of it would be immature herring.

[12] Despite the moratorium, small catches of herring were still made, e.g. as bycatches.

North Sea herring are recruited to the fishable stock at age 1. In Figure 4, recruitment in year t+1 is plotted against spawning stock in year t.[13] The plot suggests recruitment is initially increasing in SSB but eventually levels off and declines. These data will form the basis for estimation of recruitment functions in our empirical work below.

[Figure 4 here]

United Kingdom fleet and vessel economics

For the UK, pelagic trawlers over 40 m in length harvest most of the herring. These vessels are based predominantly in the north east of Scotland and in Shetland. The vessels harvest mackerel, herring and blue whiting, of which mackerel is most important in terms of both quantity and value. Mackerel and herring are mainly used for direct human consumption, while blue whiting is used for reduction into fish meal and oil. All three species represent targeted fisheries occurring in different seasons of the year and do not overlap in the catches.

North Sea herring is sold in an international market in competition with close substitutes such as Norwegian spring spawning and Icelandic herring. It is the total supply of herring of which North Sea herring is but a small part that, in conjunction with demand, will determine the price. The price of herring was increasing in the period under investigation and was recorded at £290/tonne in 2007.

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[13] The data available for analysis is annual data for the period 1960-2007 (ICES, 2007). The data includes information on recruitment, spawning stock biomass and landings. The data are available from the authors on request.

For the UK fishery, Table 1 reports available revenue data and some fleet statistics for pelagic trawl in 2007. Total landings of the pelagic trawl fleet in 2007 were 311,362 tonnes with an average value of £419/tonne. Table 1 also reports landings for each of the three species that make up total catch. In 2007, mackerel represented about 42 % of total catch quantity. Herring represented a 29 % share while blue whiting and others made up the remainder. Due to its relatively high price, the value share of mackerel is higher than the quantity share while the opposite is true for herring and blue whiting.

[Table 1 here]

Cost data are available for 2007 and reported in Table 2. Column 2 reports accounting values and column 3 opportunity values (to be explained below). The cost data represent vessel averages. In 2007, total accounting costs per vessel amounted to £3.7 million, which corresponds to £375.8 per tonne of landings. Fuel and other operating costs represented slightly over £1.5 million with crew share adding just under £1.0 million to the total costs. Average vessel accounting profit is measured at £419,921 which corresponds to £43.2/tonne.

[Table 2 here]

As indicated in Table 2, Lappo (2013) modifies the accounting data to obtain opportunity values. In the North-Sea herring fishery, labour is remunerated according to a share system and in 2007 average crew share per crewmember was £81,994. This is believed to be considerably higher than the remuneration for alternative work, which for these fishermen might be working on supply ships in the North Sea. Accordingly adjusted labour costs are set at £65,000 per man-year so that total annual labour (full-time equivalent, Table 1) costs represent £455,000 which is much less than the accounting costs. Capital costs are represented by depreciation and interest, where the latter should be estimated on the basis of the alternative or opportunity cost of capital. Opportunity capital costs are measured using the insurance value of the vessel on the assumption that this represents the alternative cost of boat and gear.[14] The interest rate is set at 5% with depreciation over 15 years. Using the annuity method, annual depreciation and interest opportunity value represent £1,235,161which is much higher than the accounting values (Table 2 column 3). Adopting these opportunity cost estimates and the previous average landings and revenue characteristics for 2007, vessel opportunity profit is considerably lower than the accounting profit or £281,812 corresponding to an average profit of £28.96/tonne.

Next, using opportunity values we estimate profits only for the herring fishery. In 2007, herring price is £290/tonne and UK herring catch is reported as 90,585 tonnes. We allocate fixed costs on a pro rata basis, i.e., according to proportion of herring in total catch (29.09% in 2007). This gives a 2007 average cost (opportunity value) of £390/tonne and results in a profit of -£9.1 million. If, on the other hand, we allocate no portion of fixed costs to the herring fishery based on an argument that it is a marginal fishery for the fleet with the mackerel fishery as the most important in terms of catches and revenue (Bjørndal 1987), this fishery would be profitable as long as revenues cover variable costs.[15] Variable costs per vessel, including repairs and maintenance, amount to £2,559,895.3 per year or £263.1/tonne. With the other assumptions in place, this would give rise to a profit for the UK herring fishery in 2007 of £2.4 million. It is interesting to

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[14] Insurance value for the vessel is only available for 2006 and valued at £12,630,800. Lappo (2013) assumes this value for 2007 adjusted for inflation.

[15] A good review of allocating costs in the public arena is found in a collection of papers edited by Young (1983).

note that, due to the sharing system in place in this fishery, some of the fishery rents accrue to the crew.

IV. THE BIOECONOMIC MODEL

The bioeconomic model employed in this paper to describe the North Sea herring fishery consists of a profit function and a biomass growth function. The profit function has already been defined in section II, equation [1]. The biomass growth function is considerably more involved as described below.

Changes in the biomass of a fish stock over time come from additions due to recruitment and natural growth, and deductions due to natural mortality and harvesting. A particular specification of these factors defines a model of biomass dynamics. Following previous bio-economic analyses of North Sea herring (Bjørndal 1987; 1988), the following delay-difference equation is used to explain changes in the North-Sea herring biomass over time:

$$S_{t+1} = (S_t - H_t)e^{\delta(S_t)} + G(S_{t-\gamma}) \qquad [11]$$

where S_{t+1} denotes spawning stock biomass in year t+1 and H_t harvest in period t, both measured in tonnes. The function $\delta(S_t)$ represents instantaneous net natural biomass growth and $G(S_{t-\gamma})$ is recruitment to the stock, taking place with delay of γ periods.

The first term on the right-hand side of equation [11] denotes stock changes due to natural growth, natural mortality, and harvesting. In the model, it is assumed that harvesting takes place during a relatively short season at the beginning of each period.

This is in accordance with the empirical facts of the North sea herring fishery.[16] The escapement, $S_t - H_t$, grows at the net instantaneous growth rate $\delta(S_t)$. This may be regarded as the difference between the rate of weight gain of living fish, *Z*, say, less their instantaneous natural mortality, *M*, both of which would normally be functions of the biomass. The second term on the right-hand side of equation [11] represents addition to the stock due to recruitment, which, again in accordance with the empirical reality of the North Sea herring stock, is assumed to occur at discrete time intervals. Moreover, recruits normally join the adult population some years, γ, after spawning.

Regarding the recruitment process, we first postulate that

$$R_{t+1} = g(S_t) \tag{12}$$

where R_{t+1} is the number of recruits to the juvenile population as a function of the previous periods spawning biomass. A certain fraction, *λ*, will survive the juvenile stage and join the spawning stock, so that

$$g(S_{t-\gamma})\lambda \tag{13}$$

is the number of recruits joining the spawning stock with a delay of γ periods. The delay occurs while the juveniles mature to spawning age. Letting *w* denote the weight of new recruits, we get the ultimate recruitment function:

$$G(S_{t-\gamma}) = g(S_{t-\gamma})\lambda w \tag{14}$$

where $G(S_{t-\gamma})$ denotes recruitment to the spawning stock. North Sea herring spawn in September and the following year recruits, called zero-group herring, join the juvenile population as indicated by equation [12]. The survivors (equation [13]) become sexually

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[16] Alternatively, it could be assumed that the fishery takes place at the end of the period, without affecting the qualitative nature of the model.

mature at age three and join the spawning or adult population (equation [14]). Thus for this species, the delay between spawning and recruitment to the spawning stock is three years. This implies that γ, i.e., the number of years from recruitment to the fishable stock and entering the spawning stock, equals 2.

Natural weight gain and mortality, Z and M, which make up the net instantaneous biomass growth, $\delta(S_t)$, in equation [11] are taken to be density-dependent; the former because there will be relatively more food available for a small stock than a large one and the latter because predation and cannibalism depend on stock size. We account for this in a general way be by defining the function $Z_t - M_t = \delta(S_t)$. Moreover we assume that the relationship is non-positive, i.e., $\delta'(S_t) < 0$.

Equation [11] is flexible enough to allow for a wide range of stock dynamics. For a constant harvest, equilibrium biomass, $\bar{S}$, is implicitly defined as:

$$\bar{S} = (\bar{S} - \bar{H}) \cdot e^{\delta(\bar{S})} + G(\bar{S}) \qquad [15]$$

For a wide range of the parameters of the two function, $\delta(.)$ and $G(.)$, equation [15] will produce a positive equilibrium and stable stock dynamics. For another set of the parameters a positive equilibrium will still exist and be stable, but the stock evolution will exhibit wide fluctuations and even be chaotic, a feature that seems to characterise the stock evolution of some small pelagic species (Hjort 1914, Hilborn *et al*. 2014).

V. MAXIMISING PROFITS

Equations [11] and [15] specify the essential structure of the bio-economic model used to describe the North Sea fishery in this study. With the functional form and parameters specified, these equations can be used to locate optimal harvesting from the North Sea herring fishery and on that basis calculate maximum profits and rents from the fishery.

The fundamental maximisation problem is to find the time path of harvests, $\{H\}$, that maximises the present value of profits for the fishery subject to the constraint given by the biomass dynamics. Formally, this problem may be written as:

$$\underset{\{H\}}{Max}\sum_{t=0}^{\infty}\pi(H_t,S_t)\cdot\alpha^t \text{ s.t. } S_{t+1}=\left(S_t-H_t\right)e^{\delta(S_t)}+G(S_{t-\gamma}),\ H_t,\ S_t \geq 0. \qquad [A],$$

where α is the discount factor defined as $\alpha=1/(1+r)$, where r is the rate of discount. [A] is a discrete time dynamic maximisation problem with H_t as a control variable and S_t as a state variable. The general solution to this problem is algebraically complicated and there is little point replicating those expressions here. In practice these kinds of problems are generally solved by numerical methods and this is what we will do in section VI below. The optimal equilibrium solution is more tractable, however, and can be expressed in a fairly informative manner.

The method of Lagrange multipliers (see Clark 1990, p. 238-9) can be used to find the optimal equilibrium solution to problem A. A Lagrangian function for problem A may be written as:

$$L=\sum_{t=0}^{\infty}\left(\pi(H_t,S_t)\cdot\alpha^t-q_t\cdot\left[S_{t+1}-(S_t-H_t)\cdot e^{\delta(S_t)}-G(S_{t-\gamma})\right]\right) \qquad [16]$$

where q_t is the Lagrange multiplier. Carrying out the maximisation and rearranging (see appendix 1), an implicit expression for the optimal equilibrium spawning stock S^* may be derived:

$$\frac{e^{\delta(s^*)}\cdot(\pi_s(S^*,H(S^*))+\pi_H(S^*,H(S^*)))}{\pi_H(S^*,H(S^*))}+e^{\delta(s^*)}\cdot\delta_s(S^*)\cdot(S^*-H(S^*))+a^{\gamma}\cdot G_S(S^*)=1+r \qquad [17]$$

where $H(S^*)$ denotes harvest in optimal equilibrium and from [15] is defined as:

$$H(S^*) = (G(S^*) - S^*) \cdot e^{-\delta(S^*)} + S^*.$$

The term $((\pi_S + \pi_H)/\pi_H)$ is the marginal stock effect (MSE) in a discrete time nonlinear model (Bjørndal 1988). The MSE, which is nonnegative, essentially represents the impact of stock size on harvesting profitability. This term, if positive, will cause an increase in the optimal stock level. Intuitively, this can be understood by realising that in this case an increase in stock size will increase catch per unit effort and hence profitability by reducing unit harvesting costs.

Compared to standard form of the optimal dynamic equilibrium solution for a fishery presented for instance in Clark and Munro (1975), expression [17] is considerably more complicated. This is entirely due to a more complicated biomass growth function in this bio-economic model. Thus, if instantaneous biomass growth and natural mortality, Z and M are equal and the time delay in the *G*(.) set to zero so that $\delta(S_t) = \gamma = 0$, it is easy to verify that expression [17] collapses to

$$G_s(S^*) + \left(\frac{\pi_s(S^*, G(S^*))}{\pi_H(S^*, G(S^*))} \right) = r \qquad [18]$$

which is exactly the traditional optimal equilibrium condition in Clark and Munro (1975).

VI. APPLICATION TO THE NORTH SEA HERRING FISHERY

The functional structure of the herring population dynamics[17] adopted in this study is a combination of the traditional dome-shaped net biomass growth function and a Ricker

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[17] Various functional forms both for stock recruitment and the net growth function have been estimated and are available from the authors on request.

stock-recruitment function (Anderson 1977, Ricker 1975). Incorporating the estimated parameters, the population dynamics are described by:

$$S_{t+1} = (S_t - H_t)e^{(0.894 - 0.39 \cdot 10^{-3} \cdot S_t)} + 1.63 \cdot 10^{-3} \cdot S_{t-2}e^{(0.96 \cdot 10^{-3} \cdot S_{t-2})} \qquad [19]$$

where biomass and harvest are measured in thousand tonnes. The carrying capacity of the biomass, $\bar{S}$, is 2,332 thousand tonnes, stock level corresponding to Maximum Sustainable Yield (MSY), S_{msy}, is 1,260 thousand tonnes with MSY at 422 thousand tonnes.

The herring population dynamics in [19] are specified as a third degree, nonlinear difference equation. To describe these dynamics succinctly, therefore, is somewhat complicated. Assuming a constant biomass, however, it is possible to graph the harvest that can be taken from the biomass on a sustainable basis. This is illustrated in Figure 5. It is noteworthy that the estimated steady-state harvest quantity is fairly constant over a wide range of stock values.

[Figure 5 here]

The harvest in period t is defined as:

$$H_t = f(K_t, S_t) = aK_t^b S_t^g \qquad [20]$$

where K_t is fishing effort in period t, and a, b and g are parameters defining the harvest production characteristics. The number of participating vessels is used as a measure of fishing effort. Parameter values for equation [20] are based on Bjørndal and Conrad (1987) and calibrated as a=0.26, b=0.95, and g=0.5621[18]. The parameter g is the output elasticity of stock size and indicates harvest will increase with stock size, but relatively

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[18] More recent estimates of the harvest function parameters are not available nor do we have available data that would allow us to estimate the parameters. It is important to note that the technological revolution in this fishery took place in the 1960s. Over the past 20 years, there have been increases in boat and engine size as well as on board processing, but the underlying technology is the same.

less than the change in stock size. The parameter *b* is the output elasticity of effort and indicates that increased effort yields increased harvest but slightly less than proportionately. This reflects the observation that the effort units (vessels) are not equally efficient in generating harvest and that the most efficient vessels are employed first.

We assume cost per unit of effort is constant. Under this assumption, we can write the cost function as:

$$C(H_t, S_t) = cK = c((1/a) * H_t S_t^{-g})^{1/b} \qquad [21]$$

where *c* is the cost per vessel per fishing season including a normal return on capital.

According to the cost data for 2007 annual operating and fixed costs for a pelagic trawler is £3,795,056.7. In 2007, herring represented 29.1% of catches. We assume that the costs in the herring fishery represent the same proportion of total cost. Thus, the cost of operating one vessel in the herring fishery for one season is £1,104,000. Moreover, we assume that cost per unit effort is constant, so effort (i.e., the number of vessels) can be increased or decreased, without impacting total vessel variable cost. On this basis and using the numerical values for *a*, *b* and *g* specified above, we can write the cost function in (21) as:

$$C(H_t, S_t) = 4{,}558{,}216 \cdot H_t^{1.0526} \cdot S_t^{-0.5917} \qquad [22]$$

Using equations [21], industry profit is defined as:

$$\pi_t = pH_t - cK_t = pH_t - C(H_t, S_t) \qquad [23]$$

where *p* is unit price of harvest. In the analysis of optimal management and of potential rents we set the price at £300/tonne, slightly above the most recent price observation (Table 1). Thus, on this basis, industry profits are:

$$\pi_t = 300{,}000 \cdot H_t - 4{,}558{,}216 \cdot H_t^{1.0526} \cdot S_t^{-0.5917} \qquad [24]$$

We will use the above profit function to describe the conditions for the entire North sea herring fishery. The assumption is that price and cost conditions for all countries participating in the North Sea herring fishery are similar to those in the United Kingdom. For output price this is reasonable as herring is sold in an international market. For costs, the same types of vessels are used in different countries and often they are built at the same shipyards. Of course, variable costs may vary across countries but we think our assumption is a reasonable approximation.

To find optimal S^* and the corresponding H^*, we solve equation [17], using the estimated model of population dynamics, [19] and the profit function, [24]. As the model is nonlinear, the solution is found by numerical methods. Results are presented in Table 3 for discount rates between zero and 10%.

[Table 3 here]

For the case with a zero discount rate, the optimal stock level is 1.392 million tonnes. Increasing the discount rate to 5% reduces the optimal level to 1.346 million tonnes. For all discount rates evaluated, S^* is greater than S_{msy} (1.260 million tonnes). It is also interesting to note that actual stock in 2005 (1.621 million tonnes) is larger than optimal equilibrium stock. On the other hand, the actual stock in 2007 (0.977 million tonnes) was much smaller than the optimal one. Optimal harvest for all discount rates is fairly stable at about 420,000 tonnes. This is because the estimated model of population dynamics yields a flat sustainable yield surface over a wide range of stock values close to the optimum (Figure 5).

The estimate of cost of effort is based on data for only one year, and it is difficult to allocate costs among the different fisheries. For this reason we will also present results on the assumption that the cost of operating one vessel in the herring fishery for one season is £1,435,200 (see equation [22]), i.e., one third higher than in the base case. The assumption of a £300/tonne price is maintained. The results are presented in Table 4. Under these alternative assumptions, optimal stock level is higher by about 40-50,000 tonnes but steady state harvest is somewhat less by about 2-4,000 tonnes.

[Table 4 here]

A sensitivity analysis shows that changes in the price of landings also have little impact on the optimal stock level and associated harvest. Thus, overall, these results are somewhat robust to changes in price and cost of effort with the optimal stock level in the range 1.3-1.4 million tonnes.

Rents and intra-marginal profits at the optimal fishery

We turn now to calculating economic rents and intra-marginal profits at the optimal stock and harvest estimates presented in Tables 3 and 4. As discussed in section II and formally expressed in equations [7] and [8], economic rents are equal to marginal profits evaluated at some harvest level multiplied by the same harvest level, while intra-marginal profits are equal to remaining variable profits evaluated at the same level of harvest. In accordance with the approach above, economic rents and intra-marginal profits are evaluated for a range of optimal stock and harvest levels depending on different discount rate and costs. The results are reported in Table 5.

[Table 5 here]

The top half of Table 5 reports results for a price of £300 per tonne and total costs of £1,104,000 per vessel. Profits in optimal equilibrium are measured at about £89 million annually and vary little across alternative discount rates. Economic rents at about £87 million makes up close to 98% of this value with intra-marginal profits measured as the residual in the order of only £1.9-2.0 million. As discussed in section II, many different variables give rise to both economic rents and intra-marginal profits. Although intra-marginal profits are small, this is what one would expect in a mature fishery. In optimal equilibrium, economic rents represent approximately 68-70% of total revenues depending on the rate of discount. This may appear high but is by no means an unusual result for commercial marine fisheries.[19]

The bottom half of the table repeats the exercise using total fishing costs increased by 1/3 amounting to £1,468,320 per vessel. In this case we observe that profits have fallen to about £77-78 million annually with economic rents representing about 97-99% of this value and about 60% of total revenues. Intra-marginal profits are now measured at about £2.5 million annually.

Rent dissipation

We are now in a position to study rent dissipation in this fishery. This is done in Table 6 with the help of four scenarios. In scenario 1, ‘actual 2007 conditions’, a total catch of 400,000 tonnes was harvested from a stock of 977,000 tonnes. With the entire pelagic fleet enjoying open access to this fishery, the 228 vessels applied to the fishery would have generated very little rents. Thus the total profits calculated at approximately £6.2

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[19] For instance it may be noted that Bjørndal (2008) found potential rents in the Norwegian spring spawning herring fishery to be 69% of revenue, based on 2006 price and cost data.

million would consist almost entirely of intramarginal profits (see table 6).[20] This scenario, of course, would not constitute a fishery equilibrium.

[Table 6 here]

In scenario 2, ‘2007 conditions with elimination of excess capacity’, we maintain the 2007 catch and stock levels but allow for elimination of excess capacity. In this scenario we allow vessels to harvest to capacity and the results show that the harvest could have been landed by as few as 38.5 boats[21] (as compared to 228 in scenario 1) which would have generated total rents of £77.5 million. As scenario 1, this is a disequilibrium scenario. The above outcomes are therefore not sustainable.

In scenario 3, ‘Optimal policy (5% discount rate)’, the optimal policy based on results from Table 5 for 5% rate of discount is adopted. In this case, the optimal sustainable stock is 1,346.2 thousand tonnes and the corresponding optimal harvest is 420.9 thousand tonnes. Compared to scenario 2, the number of vessels decreases slightly but the larger stock size combined with a higher harvest results in in a large increase in rents to £87.2 million and profits to £89.2 million.

Finally in scenario 4, 'Full rent dissipation', we work out the common pool equilibrium of the fishery. As expressed in [3] above, this is defined as biomass equilibrium such that marginal aggregate profits are zero so that there is no incentive to seek more harvest, i.e., expand effort. Note that this definition does not stipulate that profits are zero (although it implies that the marginal vessel outside the fishery cannot gain profits by entry). Since marginal profits are zero it implies, however, that economic

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[20] Assuming that the application of an excessive number of vessels to the fishery, e.g. 228, generates rents equalling *R*, it is straightforward to derive that profits will be defined by the equation: $\pi = p \cdot h \cdot (1-b) + b \cdot R$.

[21] Vessel capacity is based on existing UK technology.

rents are zero. It follows that any profits must be intra-marginal ones. As indicated in Table 6, full rent dissipation leads in equilibrium to very low equilibrium stock level and harvests.[22] The number of vessels in equilibrium is also very low and lower than that which corresponds to optimal equilibrium. The reason for this is that the low herring stock level makes it difficult for vessels to break even. All profits are intra-marginal ones and amount to about £1.4 million.

Table 6 helps in identifying the causes of rent dissipation in 2007. Moving from scenario 1 to 2 the only modification is allowing individual vessels to harvest to the capacity of their harvesting technology available given the current biomass. This requires the reduction in the fleet participating in the fishery from some 228 vessels to less than 39 vessels. From only this change we measure a twelve-fold increase in profits. Moving to optimal sustainable fisheries implies substantial investment in the stock and some increase in sustainable harvest. This will increase profits and rents but much less than removing excess capacity from the current fishery. While these results obviously depend on the particular situation of the North sea herring fishery in 2007, they suggest the more general result that in commercial fisheries, rents may often be dissipated more due to excess effort than suboptimal stock size. This would hold in particular for fisheries subject to effective biological management but weak economic fisheries management.

VI. SUMMARY AND DISCUSSION

The basic objective of this study was to obtain estimates of the current as well as potential rents in the North Sea herring fishery under different management scenarios. As a part of laying the conceptual foundation for this estimation it was necessary to

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[22] It should be noted that this equilibrium is dynamically unstable.

distinguish between rents and intra-marginal profits. This task was undertaken in section II of the paper, where, in addition, empirically applicable functional expressions for both concepts were developed. These functional expressions apply both in disequilibrium (equations [5] and [6]) and in equilibrium or a sustainable state of the fishery (equations [7] and [8]). To apply the former in empirical work, only the instantaneous profit function of the fishery has to be estimated and harvests and biomass observed. To apply the latter, both the profit function and the fish stock growth function have to be estimated, but actual harvests and biomass do not need to be observed.

The above theory was employed to calculate rents and intra-marginal profits in three economically pertinent states of the North Sea herring fishery; (i) the profit maximising equilibrium state, (ii) the competitive (or common pool) equilibrium and (iii) the fishery in 2007. Dynamic optimisation methods were used to derive an expression for profit maximising equilibrium herring stock (equation [17]). We refer to this stock level as the optimal stock. The competitive equilibrium is defined as the stock equilibrium where marginal profits are zero so there is no individual incentive to expand fishing effort. This state of the fishery is sometimes referred to as the common pool or open access equilibrium (Gordon 1954, Clark 1990). Its essence, however, is not the shared nature of the resource, but the absence of management to effectively curtail fishing effort (Bromley 1990, Ostrom 2000). Finally, it should be noted that the first two states represent stock equilibria while the third, the fishery in 2007, represents the herring stock in disequilibrium.

To obtain numerical estimates of the rents and intra-marginal rents, a bio-economic model of the North Sea herring fishery was developed. On the basis of this model, optimal stock levels were found to be in the range of 1.3–1.4 million tonnes depending on cost parameters and the rate of discount. This range of stock levels are somewhat higher than the maximum sustainable yield stock estimated to be about 1.26 million tonnes, and much higher than the 2007 stock level of 0.98 million tonnes. It is interesting to note that these optimal stock results are consistent with the North Sea herring management agreement between the EU and Norway, which expressly aims at securing a spawning stock biomass over 1.3 million tonnes.

At the optimal stock level, sustainable harvest is about 422 thousand tonnes, slightly higher than in the base year (2007) when it was about 400 thousand tonnes. Sustainable profits at the optimal stock level are estimated to be £89 million and vary little across the range of reasonable discount rates (0.035 to 0.1). Rents account for the bulk of these profits or close to 98%. The remainder, some 2% or £1.9 - 2.0 million, are intra-marginal profits. This optimal state may be compared to the actual profits in 2007 estimated at £6.2 million. It should be remembered, however, that the fishery in 2007 does not represent an equilibrium. Most likely these profits would be be further dissipated unless a more effective economic fisheries management regime were installed. In the full rent dissipation state, rents are zero. However, intra-marginal rents amount to some £1.4 million so profits are positive. This confirms earlier theoretical predictions in the literature (Copes 1972, Johnson and Libecap 1992 and Coglan and Pascoe 1999).

Another contribution of the paper is to analyse the causes of rent dissipation. Comparing the optimal state of the fishery with the one prevailing in 2007 reveals that in the latter case attainable rents have been dissipated mainly due to excess effort. While the stock in 2007 is too low compared to the optimal, the impact of this on rent dissipation is much smaller than that of excessive fishing effort. The reason for this seems to be that various harvesting controls have managed to maintain a reasonably sized biomass, while the lack of effective economic management has allowed the fishing fleet to become severely excessive. This finding is line with results other fisheries in the North Sea such as those for cod, haddock and whiting[23].

Finally, it should be noted that the bio-economic model employed to obtain the above estimates is based on the harvesting efficiency of the UK fleet. However, Norwegian and Danish vessels are also major participants in this fishery. While the UK and Norway manage their share of the fishery by vessel harvesting quotas that are largely non-transferable, Denmark operates an individual transferable quota system in its share of the fishery. As a result, the efficiency of the Danish fleet may be higher than that of the British and Norwegian fleets. If that is the case, the magnitudes of excess capacity and rent loss reported above may be somewhat overestimated. This remains an issue for further research.

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[23] See http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16857 (accessed 13.04.2016).

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Table 1
Fleet Statistics 2007

Total Landings (tonnes)	311,362
Value £, millions	130.6
Avg. value £/t	419
Landings (tonnes)	
Mackerel	132,304
Herring	90,585
Blue Whiting	56,466
Avg. value £/t	
Mackerel	663
Herring	290
Blue Whiting	119
No. of vessels	32
Crew size	12
Crew- full time equivalent	7

Source: Lappo (2013).

TABLE 2

UK Pelagic Trawl over 40m. Revenues and Costs: 2007. All values in £.

	Accounting Values	Opportunity Values
Crew	983,926.8	455,000
Fuel and other operating costs[a)]	1,534,690.8	1,534,690.8
Insurance, repairs and maintenance	570,204.5	570,204.5
Interest and depreciation on capital	568,127.2	1,235,161.4
Total vessel costs	3,656,949.3	3,795,056.7
Average cost/t	375.8	390.0
Profit	419,920.7	281,813.3
Avg. profit/t	43.16	28.96

[a)] Commission, harbour dues, subscriptions and levies, shore labour, fuel and oil, boxes, crew travel, food stores and other expenses.

Source: Lappo (2013).

TABLE 3

Estimates of optimal stock level S* (‘000 tonnes) and the corresponding harvest H* (‘000 tonnes). Price = £300/tonne. Cost per vessel per season = £1,104,000.

Discount rate	S*	H*	Vessel number
0.0	1392.0	418.25	32.75
0.035	1360.0	420.26	33.37
0.05	1346.2	420.91	33.63
0.10	1302.7	422.16	34.39

TABLE 4

Estimates of optimal stock level S* (‘000 tonnes) and the corresponding harvest H*. (‘000 tonnes). Price = £300/tonne. Cost per vessel per season = £1,468,320.

Discount rate	S*	H*	Vessel number
0.0	1,438.4	414.11	31.78
0.035	1,409.5	416.86	32.39
0.05	1,397.2	417.86	32.64
0.10	1356.2	420.45	33.44

TABLE 5

Estimates of potential rents for the North Sea Herring in £ million.

Price = £300/tonne. Cost per vessel per season = £1,104,000.

Discount Rate	Profits	Economic Rents	Intra-marginal profits	Rents/ profits
0.0	89.33	87.43	1.90	97.87
0.035	89.25	87.31	1.94	97.83
0.05	89.16	87.21	1.95	97.81
0.10	88.69	86.69	2.00	97.75

Price = £300/tonne. Cost per vessel per season = £1,468,320

Discount Rate	Profits	Economic Rents	Intra-marginal profits	Rents/ profits
0.0	77.58	75.12	2.45	96.84
0.035	77.51	75.01	2.50	96.77
0.05	77.44	74.92	2.52	96.75
0.10	77.05	74.47	2.58	96.65

TABLE 6
Rent dissipation

Scenarios	Stock size '000 tonnes	Harvest '000 tonnes	Fishing vessels	Profits (£ million)	Rents (£ million)
Disequilibrium					
1. 2007 conditions[a]	977.0	400.0	228.5	6.19	0.2
2. 2007 conditions no excess capacity	977.0	400.0	38.5	77.47	75.24
Equilibrium					
3. Optimal policy (5% discount rate)	1,341.1	421.1	33.26	89.12	87.2
4. Full rent dissipation	161.8	91.5	23.62	1.37	0

a) Estimation of vessel numbers and profits is done on an ad hoc manner based on assumptions stated in the text.

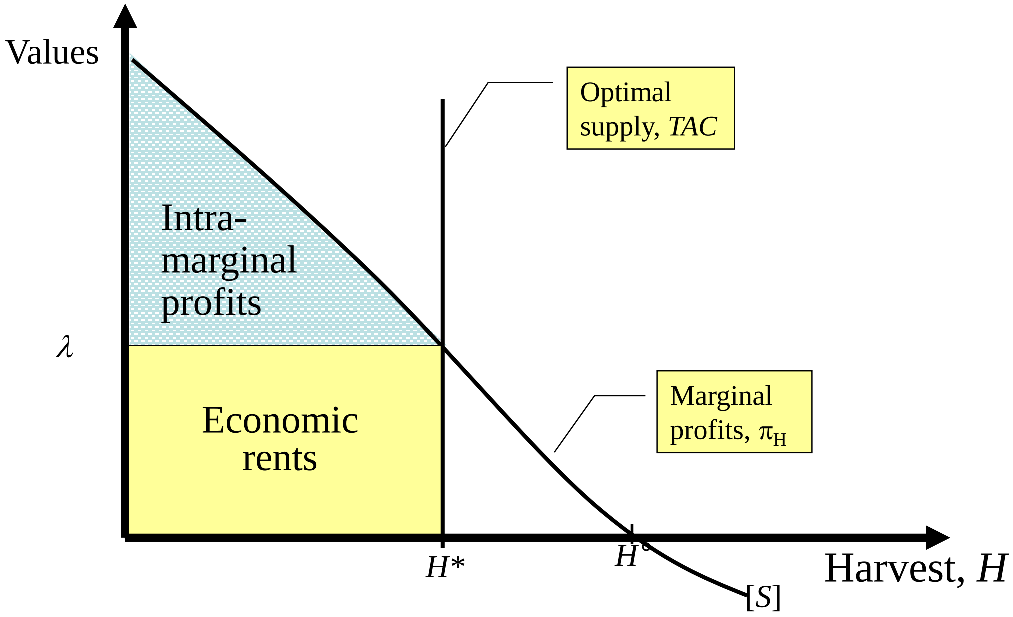

Figure 1: Rents and intra-marginal profits

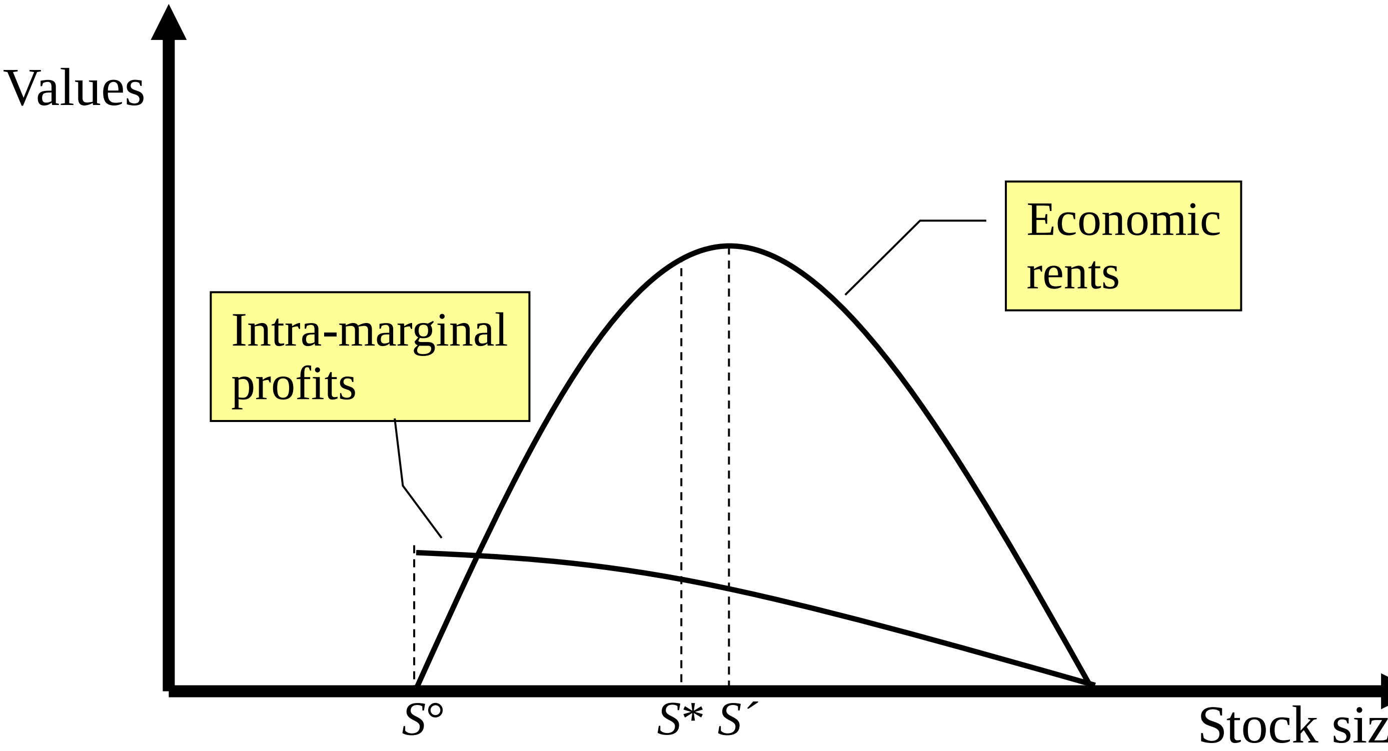

Figure 2. Equilibrium rents and intra-marginal profits as functions of stock size.

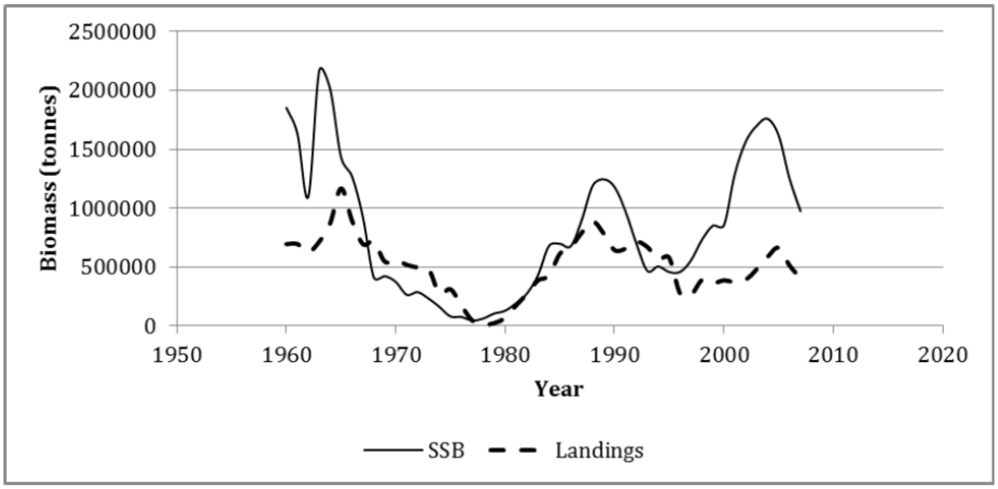

Figure 3. Spawning stock biomass and total landings 1960-2007, tonnes

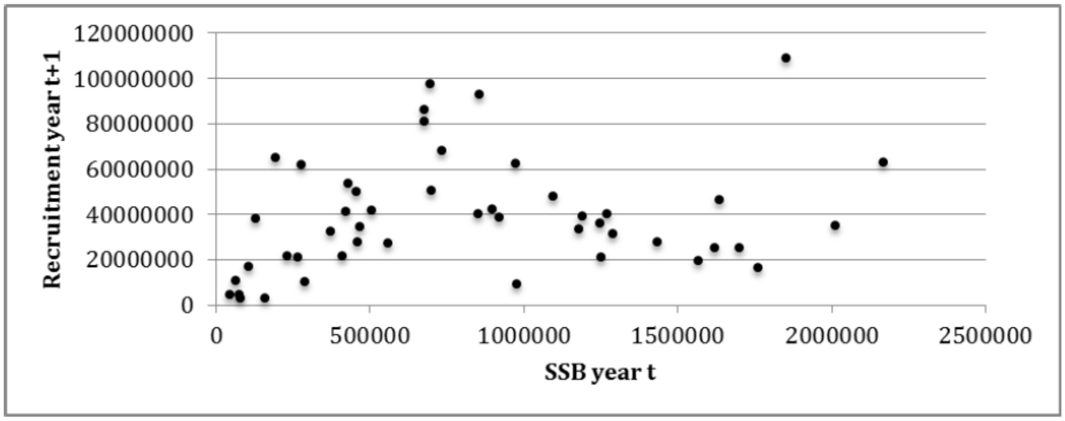

Figure 4. Recruitment in year t+1 (numbers) vs. spawning stock size in year t (tonnes)

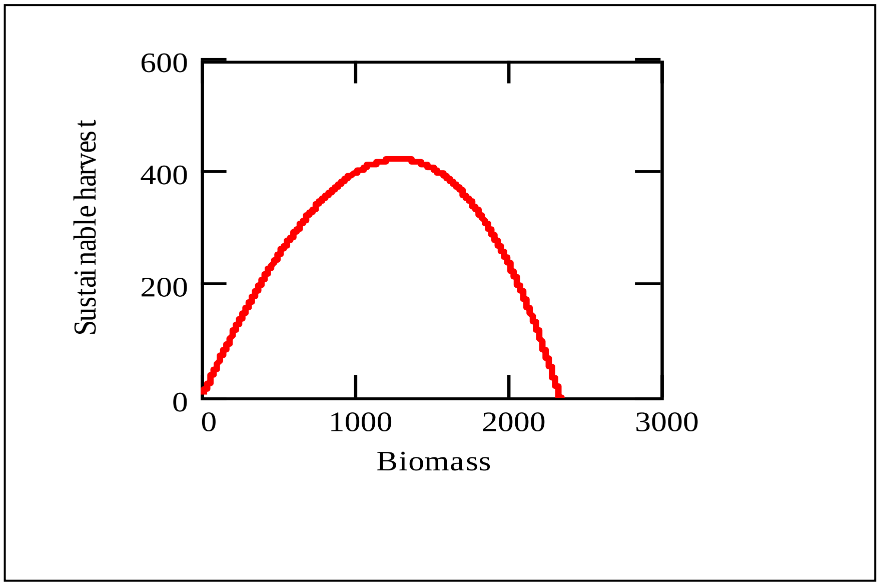

Figure 5. Sustainable harvest (1000 metric tonnes)

Appendix 1

Derivation of the optimal equilibirum condition, equation (17)

The problem is to maximise the present value of profits

$$\underset{\{H\}}{Max}\sum_{t=0}^{\infty}\pi(H_t,S_t)\cdot\alpha^t \text{ s.t. } S_{t+1}=\left(S_t-H_t\right)e^{\delta(S_t)}+G(S_{t-\gamma}),\ H_t,\ S_t \geq 0,$$

where H_t and S_t denote harvest and biomass at time *t*, respectively and α is the discount factor defined as $\alpha=1/(1+r)$, where *r* is the rate of discount. A Lagrangian function corresponding to this problem may be written as:

$$L=\sum_{t=0}^{\infty}\left(\pi(H_t,S_t)\cdot\alpha^t-q_t\cdot\left[S_{t+1}-(S_t-H_t)\cdot e^{\delta(S_t)}-G(S_{t-\gamma})\right]\right)$$

Differentiating this function with respect to H_t and S_t and setting the derivatives equal to zero yields the necessary conditions for solving the maximisation problem:

$$\pi_{H_t}(H_t,S_t)\cdot\alpha^t=q_t\cdot e^{\delta(S_t)}\text{, all } t,$$

$$\pi_{S_t}(H_t,S_t)\cdot\alpha^t+q_t\cdot e^{\delta(S_t)}+q_t\cdot(S_t-H_t)\cdot\delta_{S_t}(S_t)\cdot e^{\delta(S_t)}-q_{t-1}+q_{t+\gamma}\cdot G_{S_t}(S_t)=0\text{, all } t.$$

The first of these conditions implies:

$$q_t=\pi_{H_t}(H_t,S_t)\cdot e^{-\delta(S_t)}\cdot\alpha^t$$

$$q_{t-1}=\pi_{H_{t-1}}(H_{t-1},S_{t-1})\cdot e^{-\delta(S_{t-1})}\cdot\alpha^{t-1}$$

$$q_{t+\gamma}=\pi_{H_{t+\gamma}}(H_{t+\gamma},S_{t+\gamma})\cdot e^{-\delta(S_{t+\gamma})}\cdot\alpha^{t+\gamma}$$

Substituting these expressions into the second necessary condition and adding the equilibrium conditions that equilibrium values of biomass are constant and

$$S^*=\left(S^*-H^*\right)e^{\delta(S^*)}+G(S^*),$$

where "*" indicates equilibrium values and rearranging yields the optimal equilibrium solution:

$$\frac{e^{\delta(S^*)}\cdot(\pi_S(S^*,H(S^*))+\pi_H(S,H(S^*)))}{\pi_H(S^*,H(S^*))}+\delta'(S^*)\cdot e^{-\delta(S^*)}\cdot(S^*-G(S^*))+\alpha^{\gamma}\cdot G'(S^*)=1+r$$

.