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Towards the Optimal Management of the Northeast Arctic Cod Fishery

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Summary

The objectives pursued by governments managing fisheries may include maximizing profits, minimizing the impact on the marine ecosystem, or securing employment, which all require adjusting the composition of the fishing fleet. We develop a management plan that can be adapted to those objectives and allows the regulator to compare the long-run profits between the various management options. We apply the model to the case of Northeast Arctic cod, and estimate the cost and harvesting functions of various vessel types, the demand function, and a biological model to provide key insights regarding the optimal management of this valuable fish species.

Keywords: Northeast Arctic Cod, Norway, Production Functions, Harvest Control Rule, Fleet Structure, Multiple Objectives

JEL Classification: C10, Q21, Q22, Q28

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Towards the Optimal Management of the Northeast Arctic Cod Fishery

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Abstract:

The objectives pursued by governments managing fisheries may include maximizing profits, minimizing the impact on the marine ecosystem, or securing employment, which all require adjusting the composition of the fishing fleet. We develop a management plan that can be adapted to those objectives and allows the regulator to compare the long-run profits between the various management options. We apply the model to the case of Northeast Arctic cod, and estimate the cost and harvesting functions of various vessel types, the demand function, and a biological model to provide key insights regarding the optimal management of this valuable fish species.

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I. Introduction

Fisheries management has never been easy, but today's challenges are larger than ever before. Globally, 80 percent of marine fish stocks are maximally exploited or even overexploited (FAO, 2008), and several stocks have already collapsed (Jackson et al., 2001). At the same time, more people rely on seafood as a major source of protein, especially in developing countries (Smith et al., 2010). Sustainability may rank high on the policy makers' agenda, but the profitability of the fisheries sector does so too, and the same holds for employment opportunities. As these objectives can never be fully achieved simultaneously, there is a tendency among economists to focus on one single easy objective (maximum economic rent), while deemphasizing the importance of the other objectives (Dichmont et al., 2010; Grafton et al., 2010; Grafton et al., 2007). Therefore, it has been suggested that successful fisheries management is largely a question about transparency and congruency of objectives (Dankel et al., 2008; Hilborn, 2007; Squires, 2009). In principle, there are two potential ways to give policy recommendations when facing multiple objectives; see Banzhaf (2009). The first approach assumes that the relative shadow prices of financial, environmental and social objectives are known so that their weighted sum can be maximized. The second is that the researcher just presents the trade-offs and leaves it to the policy process to decide what actions foster social welfare.

In this paper we take the second approach as we analyze how a fishery should be managed in the light of multiple policy objectives. We identify the optimal fleet structure for various objectives by maximizing economic rent with and without explicit constraints on fleet activity – depending on environmental or social considerations. We apply our analysis to one of the world's most important fisheries: the stock of Atlantic cod *(Gadus morhua)* in the Northeast Arctic, along the coast of Norway and in the Barents Sea. This is the world's largest stock of cod, and the history of the Northeast Arctic (NEA) cod fishery since World War II is one of continued increases in landings, suddenly giving way to a near collapse of the fishery in 1989. In response to the cod crisis, a management regime was introduced that imposed a fishing quota on each ocean-going vessel in the industry. The question is how to allocate those quotas most efficiently and – even more important – how to set a total allowable catch (TAC) to prevent another cod crisis while meeting broader management objectives. Fisheries management in Norway has a long tradition and regulations and management objectives have changed considerably over time (Årland and Bjørndal, 2002; Hannesson, 2004; Hersoug, 2005; Holm, 1995; Nakken et al., 1996). Årland and Bjørndal (2002) have identified the main objectives of Norwegian fisheries regulations as (i) increasing the profitability of the fisheries sector, (ii) protecting the resource base, and (iii) securing employment opportunities in coastal communities to maintain the settlements along the coast.

In this paper we determine the optimal TAC as well as the most efficient allocation of individual catch quotas over the various types of fishing vessels for various management objectives: (i) we analyze the scenario that the policy maker intends to maximize simply the rents from the fishery – harvesting should take place at lowest costs. (ii) we consider the case that a policy maker maximizes rents on the condition that only boats are used that have least impact on the ecosystem. (iii) we take into account that a diverse fleet is preferred (for the sake of regional development and cultural diversity). For all of these objectives, we determine the optimal TAC as well as the most efficient allocation of individual catch quotas over the various types of fishing vessels for various management objectives including maximization of the rents of cod harvesting.

Although the stock of NEA cod lies within the exclusive economic zones of both Russia and Norway, we focus our analysis on the Norwegian fishing fleet of ocean-going vessels, because it consists of a wide variety of boat types including trawlers, factory trawlers and longliners (Sandberg, 2006; Standal, 2008). Hence, determining the optimal fleet composition for the various management objectives is complex. We develop an analytical model to derive the optimal levels of biomass and the associated TAC, and estimate all parameters of the model using data on the NEA cod fishery. More specifically, we estimate the cost and production functions of the various vessel types in the industry (trawlers, longliners and factory trawlers), the demand function for cod (to determine how its value changes with quantity supplied), as well as the parameters of the growth function of cod.

This study has several unique features. First of all, it takes into account the many problems associated with estimating the harvesting, cost, growth and demand functions including serial correlation and endogeneity. In this respect we improve on the earlier work by Arnason et al. (2004) and Kugarajh et al. (2006) in estimating the demand function for cod, and by explicitly acknowledging that there are not only variable costs associated with harvesting cod, but that there are fixed costs too (Asche, 2009). Second, we combine the empirically estimated functions into a model which allows policy makers to infer (i) the steady-state levels of biomass that maximize their objectives (either unconstrained rent maximization, or rent maximizations taking into account environmental and/or social constraints), (ii) the associated optimal TAC and the allocating thereof over the various vessel types, and (iii) the optimal harvest control rule (HCR) that informs the decision maker about the optimal TAC and its allocation over the boat types for every level of biomass – independent of whether it is the optimal steady-state stock, or not. Third, our study also provides a flexible framework to include constraints regarding the supply side of fleet composition – the fact that a cost-minimizing long-run strategy cannot be implemented instantaneously, as boats that operate at lower costs cannot replace more costly ones in the short-run. As a result, our model provides an important bridge between analytical fisheries models that have little empirical content, and highly detailed econometric studies that do not deliver any direct policy advice.

While an optimal allocation between the coastal and the ocean-going fleet has received some attention in the literature (Armstrong, 1999, 2000; Armstrong and Sumaila, 2001), the size of an optimal individual quota per boat is usually not addressed. This is somewhat surprising, given that the question how to allocate a TAC over a certain number of boats is one of the most obvious management problems a fishery faces. An exception is Asche et al. (2009) who have addressed this question for the Norwegian trawler fleet. In most bioeconomic models individual boats do not exist – often costs are estimated at the aggregated level and hence, the fleet can only be analyzed as one entity; see Bromley (2009). This is an obvious shortcoming, as increasing and decreasing returns to scale operate at the boat level – not at the industry level. It is sometimes argued that a policy maker does not need to worry about how to distribute harvesting rights because a market for individually tradable quotas will ensure the efficient allocation (Grafton et al., 2006; Hannesson, 2004). We would like to note that this is not true for two reasons. First, the total quota size to be allocated (via grandfathering, or via auctions) crucially depends not just on the benefits of selling cod (in terms of revenues obtained), but also on the costs of harvesting it. While the benefits only depend on the quantity supplied to the market (i.e., on the TAC), the costs critically depend on the composition of the fishing fleet as some boat types are more efficient in catching cod than others. Hence, while a system of ITQs may ensure that actual harvesting takes place at minimum cost, we still need to know how the minimum cost solution looks like in order to decide on the level of the TAC itself. Second, even if ITQs result in fishing activity that operates at least costs, such an outcome would only be socially optimal if society had no other objectives than just minimizing harvesting costs. In reality, broader objectives, such as ecosystem preservation, the cultural value of a diverse fleet, or equity considerations, are pursued. Therefore, in this case detailed information on the various vessel types is needed to be able to determine whether or not certain boat types should be prohibited from purchasing ITQs.

Management of the NEA cod fishery is inherently complex, and any useful model – as the one developed here – has inevitably to sacrifice certain details. First of all, this study ignores important ecosystem effects. At the end of the year, the mature fish migrate out of the Barents Sea for about 3 months to spawn, returning to the feeding grounds in spring. The cod eggs drift up along the Norwegian coast and the immature fish stay in the feeding grounds until maturation when they start reproducing. Obviously management could be substantially improved by acknowledging the age-structure and the productivity of the stock (Diekert et al., 2010a; Sumaila, 1997a). Second, and in a similar vein, the fact that older cod tend to cannibalize on younger cod may have management implications that are ignored here (Armstrong, 2000; Armstrong and Sumaila, 2001). Third, if harvesting pressure is very high this may induce an evolutionary response that leads to economic repercussions (Eikeset et al., 2010b). Fourth, food-web interactions with other species are important factors driving the cod stock dynamics. For example capelin (*Mallotus villosus*) and Norwegian Spring-Spawning (NSS) herring (*Clupea harengus*) are two of the most important fish species the cod interacts with (Hjermann et al., 2007). Herring feeds on capelin larvae (Gjøsæter and Bogstad, 1998) and is therefore competing with the cod for the prey species capelin. We ignore this effect in this paper, but see (Link and Tol, 2006; Sumaila, 1997b). Fifth, climate plays also an important role in this ecosystem. If new species immigrate from the south, this leads to a new food-web structure (Ottersen et al., 2006). Examples of bioeconomic models that have analyzed how climate may affect the management of cod are Hannesson (2007b) and Link and Tol (2009). A study that takes both climate change and multiple species into account is Eide and Heen (2002). Sixth, climate change may also affect the negotiations and the legitimacy of the Joint Norwegian-Russian Fishery Commission. If the climate gets warmer, this may trigger capelin to migrate further into Russian waters in which the cod may follow (Roderfeld et al., 2008). Our analysis does not touch upon such strategic interactions, as we assume that the management authority in place sets and enforces the quota; see for examples of strategic games regarding the NEA cod fishery, Diekert et al. (2010b), Hannesson (2007a), and Sumaila (1997a; 1997b).

This paper is organized as follows. In section 2 we present an overview of the NEA cod fishery. Section 3 develops the optimal management plans for a variety of management objectives. We estimate the model in section 4, presenting the parameterizations of the production, cost, and demand functions as well as of the biological model. Next, section 5 combines the theoretical and empirical results and derives an optimal policy, while section 6 concludes.

II. The Northeast Arctic cod Fishery

The NEA cod fishery consists of two parts that are geographically separate: the feeding grounds in the Barents Sea, and the spawning grounds further south along the coast of Norway. Norwegians have been fishing for over thousands of years in predominantly the spawning grounds because of their proximity to villages and ports. Since the 1930s (and especially after the second world war), technological developments facilitated the use of large ocean-going trawlers in the feeding grounds in the Barents Sea, which resulted in an increase in fishing pressure

(Godø, 2003). Until the early 1970s the number of trawlers steadily increased and landings have been as high as one million tonnes per annum – for some years, the harvesting probability for individual fish was as high as 70% per year (Eikeset, 2010).

In the late 1970s it became clear that the NEA cod fishery was overexploited; see Figure 1. In 1977 the Norwegian government responded by starting to actively enforce the country's exclusive economic zone and by barring the entry of new trawlers (Standal and Aarset, 2008). Also, a cap was introduced on the total amount of cod caught per year (the so-called total allowable catch, or TAC). Unfortunately, the TACs in the 1980s were too lenient to prevent the cod crisis that occurred in 1989 – especially because the cod was under severe stress already due to the population collapse of one of its main prey species, capelin.

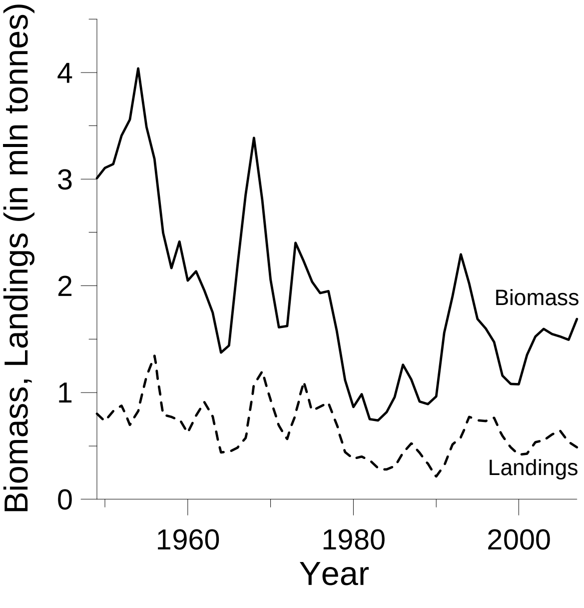

Figure 1. The data on total landings (dotted line) and corresponding total biomass (solid line) of Northeast Arctic cod from 1949-2007. Data are obtained from ICES (International Council for the Exploration of the Seas)

As a consequence the TAC in 1989 had to be reduced dramatically with disastrous consequences for the cod fishing industry (Hersoug et al., 2000). To deal with the crisis, a system was introduced that gave each ocean-going vessel in the industry a quota to catch a certain amount of cod. These quotas were non-transferable at first, but later on the regulations were revised to allow vessels to transfer harvesting rights (Hersoug et al., 2000; Holm and Nielsen, 2007; Standal and Aarset, 2008). Currently, the fishery is managed by the Joint Norwegian-Russian Fishery Commission as the feeding grounds of NEA cod (in the Barents Sea) are located in the exclusive economic zones of both countries.

III. The optimal management of the cod fishery

We assume the government aims to maximize the net present value of economic rents as the sole-owner of the resource. Because about 90% of the cod is exported, rent maximization can best be described by maximizing profits – consumer surplus can be ignored because the Norwegian government is likely to attach little weight to the consumer welfare accruing to citizens outside Norway (but see footnote 9). However, we acknowledge that society may have broader objectives than just maximizing rents from harvesting cod. These other considerations may be related to environmental concerns (as some boat types are more damaging to the marine ecosystem than others) or social-cultural concerns (the desire to maintain a diverse fleet because of cultural considerations). Therefore, we assume that the government aims to maximize Norway’s rents of cod harvesting while it may or may not decide to impose constraints on the type of vessels used to address these other considerations too.

Deriving an optimal TAC

We derive the optimal management plan for three different management objectives. First, we solve the problem assuming that society chooses to use a fleet that is able to harvest a specific amount of cod, the TAC, at least total costs. Second, we consider the case in which society imposes additional constraints on the fleet composition in order to protect the marine environment by banning trawlers and factory trawlers, since they are deemed more destructive to the ecosystem than longliners (Dayton et al., 1995). The third case we consider is the one where the government, motivated by employment or cultural considerations, decides to maintain a diverse fleet by allocating harvesting rights to a variety of vessel types in the industry – as is currently done in the Norwegian cod fishery. Throughout the paper, we follow Salvanes and Squires (1995) by assuming that all boats of a specific type are identical.

The instantaneous flow of economic profits, Π_t, is specified as follows

$$\Pi(X_t, TAC_t) = R(TAC_t) - C(X_t, TAC_t), \qquad [1]$$

where X_t is the biomass of cod present in the Northeast Arctic in year t, and TAC_t is the total allowable catch set by the government. Furthermore, $R(TAC_t)$ are the revenues of supplying TAC_t to the market, and $C(TAC_t, X_t)$ are the costs of catching TAC_t. The cost function is assumed to be a function not only of the quantity harvested, but also of the amount of cod biomass remaining. The reason is that the returns per unit of effort (for example, the number of days spent catching cod) may depend on the density of the fish in the sea (the so-called stock effect). Also note that the costs of catching fish are obviously also dependent on the types of vessels used – in other words, they depend on the implemented policy concerning the fleet composition. In section 4, the empirical estimations show that $C_X < 0$ and $C_{TAC} > 0$.[1] Regarding the revenue function, we assume a linear inverse demand function for cod:

$$P_t = a - bTAC_t, \tag{2}$$

so that $R(TAC_t) = (a - bTAC_t)TAC_t$. The optimal control problem the government faces is as follows:

$$W = \max_{TAC} \int_0^{\infty} e^{-\delta t}\Pi(X_t, TAC_t)dt \tag{3}$$

subject to

$$\dot{X}_t = G(X_t) - TAC_t, \tag{4}$$

where dots denote time derivatives, δ is the discount rate, and $G(X)$ is the growth function of the cod stock, which is assumed to be logistic:

$$G(X_t) = rX_t\left(1 - \frac{X_t}{K}\right), \tag{5}$$

where r is the intrinsic population growth rate, and K is the maximum amount of cod biomass that would materialize in the long run absent harvesting – the so-called carrying capacity. The current-value Hamiltonian $\mathcal{H}$ is then given by[2]

$$\mathcal{H} = (a - bTAC)TAC - C(TAC, X) + \varphi\left[G(X) - TAC\right], \tag{6}$$

where φ is the co-state variable.

Using the dynamics of the resource stock [4] and applying the maximum principle, we obtain the following first-order conditions for an optimum:

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[1] Partial derivatives are denoted by subscripts, and hence $C_X \equiv \partial C / \partial X$.

[2] In the rest of the paper we omit time subscripts unless doing so could cause confusion.

$$\mathcal{H}_{TAC} = 0 \quad \Rightarrow \quad \varphi = a - 2bTAC - C_{TAC}, \qquad [7]$$

$$\delta\varphi = \dot{\varphi} - C_X + \varphi\ G_X. \qquad [8]$$

To derive the steady-state optimum, we set $\dot{\varphi} = \dot{x} = 0$. Subsequently substituting [7] into [8] we have:

$$TAC = \frac{\left(2rX + K\left(\delta - r\right)\right)\left(a - C_{TAC}\right)}{2b\left(2rX + K\left(\delta - r\right)\right) + KC_X}. \qquad [9]$$

As shown in [9], the optimal *TAC* depends on the cost function, and hence on the composition of the fleet – as not all vessel types are likely to be equally efficient in catching cod. While C_X (the stock effect) is transmitted through all vessels that are in operation, C_{TAC} (the cost of catching an additional tonne of cod) is only transmitted through the marginal vessel type: the type that is the last to receive a quota if these quotas are handed out starting with the most preferred type. This difference is important if more than one vessel type is in use for catching cod. If only one boat type is operated in the cod fishery, deriving C_{TAC} and C_X is straightforward. This may be the case because one vessel type outperforms all other types in a specific aspect – one type may be able to harvest at lower costs than the others, or one type may have smaller environmental impacts than any of the other types. If, however, more than one type is used in the fishery (because the government values a diverse fleet because of social or cultural considerations, or because it faces constraints regarding the number of vessels of the preferred type), the stock effect C_X shows the impact of having an extra tonne of biomass on *all* vessels (of all types used) in the fishery. C_{TAC} on the other hand only pertains to the marginal boat type as defined above. Furthermore, because the optimal TAC depends on the composition of the fishing fleet, so does the optimal steady-state biomass, which can be determined by substituting [4] into [9] and solving for X. Having determined the optimal stock and harvesting levels, we can also calculate economic rent (as measured by economic profits).

While steady-state biomass and harvest levels are interesting in itself, they are often not very useful for management purposes, as in reality the stock will never be in steady state. Therefore, we derive a harvest control rule (HCR) that informs the decision maker about the optimal TAC for any given stock level. A feedback HCR can be determined relatively easily following Sandal and Steinshamn (1997a; 2001); see for applications Arnason et al. (2004) or Grafton et al. (2000). From [7] it follows that the co-state variable φ can be rewritten as a function of the state and the control variable (X and TAC, respectively). If the discount rate is zero, the Hamiltonian is constant over time, and maximizing the current-value Hamiltonian boils down to maximizing the profit flow (as defined in [1]) that can be obtained in a steady state, also referred to as the sustainable economic rent $\Pi^*(X)$ (Sandal and Steinshamn, 2001).[3] We thus obtain the following analytical feedback rule:

$$TAC = \frac{2brX\left(1-\frac{X}{K}\right) \pm \sqrt{\left(-2brX\left(1-\frac{X}{K}\right)\right)^2 - 4b\left(\left(a-C_{TAC}\right)rX\left(1-\frac{X}{K}\right)-\Pi^*(X)\right)}}{2b}; \qquad [10]$$

see Appendix 1 for the exact derivation. Both $\Pi^*(X)$ and C_{TAC} depend on the fleet structure. In section 5, we show how much the optimal long-term policy given by [9] and short-term policy given by [10] are affected by the chosen fleet structure.

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[3] The results in section 5 show that optimal long-run policy is very insensitive to different discount rates. Given that discounting is even less important in the short run, a positive discount rate will most likely not have a considerable impact on the results; see also Sandal and Steinshamn (1997b).

Deriving the optimal quota allocation for each individual vessel type

Suppose that currently there are Z different types of vessels used in the industry, such as trawlers, factory trawlers, and longliners. Furthermore, in this subsection we also assume that boats can freely enter or leave the cod fishery at no cost – an assumption that will be relaxed later. The total allowable catch of the vessels of type z, $z \in [1,..,Z]$, in year t is denoted by TAC_{zt}, and the sum of these type-specific allowable catches should add up to the TAC as determined by the government for that year (that is, $TAC_t = \sum_{z=1}^{Z} TAC_{zt}$). The production process of a vessel of type z is described by a Cobb Douglas harvest function. Here, the amount of cod harvested in year t (h_{zt}) is a function of both that vessel's effective fishing effort (e_{zt}) and the total amount of cod biomass (X_t):

$$h_{zt} = q_z X_t^{\alpha_z} e_{zt}^{\beta_z}, \qquad [11]$$

where q_z is a catchability coefficient, α_z is the stock-output elasticity and β_z is the effort-output elasticity. All parameters are boat type-specific, and α_z and β_z reflect the percentage increase in harvests resulting from a one percent increase in the relevant input. In section 4 we show that for all boat types, $1 > \beta_z > \alpha_z > 0$. Finally, e_{zt} is measured by the number of days catching cod multiplied by the vessel's Gross Real Tonnage (GRT). That is, effort is measured in efficiency units – tonnage days.

Regarding the costs of catching cod, we distinguish between fixed costs and variable costs. Fixed costs include adjustment costs, such as changing the vessel's gear to make it suitable for catching cod, but also the fuel spent on sailing to the cod fishing grounds, etc., while the variable costs are the costs incurred on the days that the vessel is actually catching cod. We use f_z to denote the fixed cost components while the variable costs of effort are assumed to be constant and equal to v_z. Hence, the annual costs incurred by a vessel of type *z* spending e_{zt} tonnage days catching cod in a year are given by

$$c_{zt} = f_z + v_z e_{zt}. \qquad [12]$$

Let us first determine, for each vessel type *z*, the optimal effort level per boat e_z^*, and also the optimal number of boats n_z^*, if the aggregate amount of cod to be caught by all boats of type *z* is equal to TAC_z (that is, $n_z q_z X^{\alpha_z} e_z^{\beta_z} = TAC_z$). The Lagrangian of the cost minimization problem is as follows:

$$\Phi_z = n_z \left(v_z e_z + f_z \right) + \lambda_z \left(TAC_z - n_z q_z X^{\alpha_z} e_z^{\beta_z} \right), \qquad [13]$$

where λ_z is the shadow price of harvesting an extra tonne of cod by increasing the fleet size or the size of the quota per boat. The first order conditions associated with [13] are

$$\frac{\partial \Phi_z}{\partial n_z} = v_z e_z + f_z - \lambda_z q_z X^{\alpha_z} e_z^{\beta_z} = 0, \qquad [14a]$$

$$\frac{\partial \Phi_z}{\partial e_z} = n_z v_z - \beta_z \lambda_z n_z q_z X^{\alpha_z} e_z^{\beta_z - 1} = 0, \qquad [14b]$$

$$\frac{\partial \Phi_z}{\partial \lambda_z} = TAC_z - n_z q_z X^{\alpha_z} e_z^{\beta_z} = 0. \qquad [14c]$$

For future reference, it is convenient to note that [14a] implies that the shadow price is equal to the vessel's average costs of catching cod fish:

$$\lambda_z = \frac{v_z e_z + f_z}{q_z X^{\alpha_z} e_z^{\beta_z}}. \qquad [15]$$

Next, combining [14a] and [14b] we find that the optimal amount of effort per vessel per year is equal to

$$e_z^* = \frac{f_z\beta_z}{v_z\left(1-\beta_z\right)}. \qquad [16]$$

This efficient scale of operating a vessel of type *z* is the result of two competing effects associated with increasing the amount of cod harvested. If h_z is increased, the fixed costs of adjusting the gear to cod harvesting (f_z) are spread over a larger harvest, but increasing h_z also requires a more than proportional increase in effort (e_z) because of decreasing returns to scale; see [11]. Hence, the average costs of harvesting cod per vessel are a U-shaped function of effort, with its turning point at e_z^*. Also, note that the efficient scale of employing a boat of type *z* is constant and independent of biomass. Let us now proceed by calculating the costs per vessel operating at e_z^* tonnage days of catching cod. Using [12] and [16] we have

$$c_z^* = f_z + v_z e_z^* = f_z + v_z\left(\frac{f_z\beta_z}{v_z\left(1-\beta_z\right)}\right) = \frac{f_z}{\left(1-\beta_z\right)}. \qquad [17]$$

Next, substituting [16] into [14c], we find that the optimal number of boats of type *z* is equal to

$$n_z^*\left(TAC, X\right) = \left(\frac{v_z\left(1-\beta_z\right)}{f_z\beta_z}\right)^{\beta_z}\frac{TAC_z}{q_z X^{\alpha_z}}. \qquad [18]$$

The larger the amount of biomass, the more productive is a boat of type *z*, and hence the fewer boats are needed to harvest a specific TAC. So, combining [17] and [18] we identify that the harvesting costs of all boats of type *z* operating at the efficient scale are equal to

$$C_z\left(TAC_z, X\right) = n_z^* c_z^* = \Omega_z TAC_z / X^{\alpha_z}, \qquad [19]$$

where $\Omega_z \equiv q_z^{-1}(v_z/\beta_z)^{\beta_z}(f_z/(1-\beta_z))^{1-\beta_z}$. When operating at the optimal scale, the average costs of catching one tonne of cod fish are equal to

$$\lambda_z^* = \tilde{c}_z = \frac{\Omega_z}{X^{\alpha_z}}. \qquad [20]$$

Determining the optimal allocation of vessel quotas

We analyze the case where the government (i) chooses to use a fleet that operates at lowest costs (potentially the result of a market mechanism like an ITQ system in which boats of all types are allowed to participate) or (ii) takes broader objectives into account and imposes fleet constraints.

First, we assume that the government aims to minimize the costs of catching a certain amount of cod, the TAC. From [19] it is clear that this would require allocating the entire TAC quota to the vessel type that, for the relevant level of biomass, has the lowest average harvesting costs, $\tilde{c}_z = \Omega_z / X^{\alpha_z}$; see [20]. Let us use subscripts $z = LC1$ to denote the vessel type with the lowest average costs, $z = LC2$ to denote the vessel type with the one-but-lowest average costs, etc. More formally, $z = LC1$ is defined as the type for which we have $\tilde{c}_{LC1} = \Omega_{LC1} / X^{\alpha_{LC1}} \leq \Omega_z / X^{\alpha_z} = \tilde{c}_z \quad \forall \quad z = \{1,..,Z\}$, $z = LC2$ is defined as the type for which we have $\tilde{c}_{LC2} \leq \tilde{c}_z \quad \forall \quad z = \{1,..,Z\} \setminus \{LC1\}$, and so on.

Second, we assume that governments may pursue objectives other than just pure financial profit maximization. While pure cost minimization may dictate $TAC_z = 0$ for all $z \neq LC1$, considerations other than the concern for financial cost minimization may result in $TAC_z = \theta_z TAC > 0$ for at least some $z \neq LC1$ too. Rather than to solve the optimization problem taking these considerations into account, we just assume that the government chooses a specific vector of shares $(\sum_{z=1}^{Z} \theta_z = 1)$, and then determines the optimal TAC within these quotas constraints $TAC_z = \theta_z TAC$.

This approach allows the government to calculate the costs associated with imposing an allocation of quotas other than the allocation that minimizes harvesting costs. The difference in economic profits indicates the costs to society for not using the cost-minimizing vector of shares so that these costs can subsequently be compared, explicitly or implicitly, to the environmental or social benefits obtained, to decide whether the benefits of these decisions exceed their costs. While allocation of quotas *between* several fleet types is not necessarily cost-minimizing (as it may be determined by other policy objectives than just maximizing financial welfare), the quota allocation *within* a fleet is still assumed to be optimal – and given by the number of tonnage-days boats spend catching cod (e_z^*). For any given vector of shares θ_z and TAC, from [19] we have that the total harvesting costs are then equal to

$$C^*(TAC, X) = \sum_{z=1}^{Z} \left(\Omega_z \theta_z TAC / X^{\alpha_z} \right). \qquad [21]$$

Note that [21] allows the government to calculate the (marginal) harvesting costs for all possible management objectives. In case it attempts to maximize fleet profits, the cost-minimizing allocation can be recovered from [21] when setting $\theta_{LC1} = 1$ and $\theta_z = 0 \;\; \forall \;\; z = \{1,..,Z\} \setminus \{LC1\}$. If environmental concerns play the key role, [21] gives the associated cost function setting $\theta_z = 1$ for the boat type that is considered least harmful (and zero shares to all other vessel types). In short, the government can simply insert the vector of harvesting shares it deems optimal into [21] to obtain the associated harvesting cost function.

Optimal quota allocation in case of fleet lock-in

In the previous sub-section, we have shown that it is cost-minimizing to use only the vessel type that has the lowest average costs. In practice, one is typically confronted with a situation where boats of a specific type cannot easily replace vessels of a different type. Instead, the fleet composition can only be changed in the short run at substantial costs – a situation which we will refer to as a fleet lock-in. In this sub-section, we analyze how to allocate a TAC if there are maximally $\overline{n}_z$ vessels of type z available in the industry. We keep the assumption that boats can be employed in a different fishery, but the maximum number of vessels of type z is given by $\overline{n}_z$. In that case, [16] and [18] can only be implemented if $n_z^* \leq \overline{n}_z$. The cost-minimizing policy in case of lock-in can then be derived as follows. First, one needs to calculate the maximum amount of cod that can be caught by the vessel type with the lowest average costs $(z = LC1)$ when all $\overline{n}_z$ boats of that type are run at their efficient scale e^*_{LC1} (as given by [16]):

$$\overline{TAC}_{LC1}\left(X\right) = \overline{n}_{LC1} q_{LC1} X^{\alpha_{LC1}} \left(e^*_{LC1}\right)^{\beta_{LC1}}. \qquad [22]$$

If $TAC \leq \overline{TAC}_{LC1}$ all harvests can be caught by the vessels with the lowest costs at optimum effort level e^*_{LC1}. In that case, it is optimal to have each individual boat being run at its efficient scale, and that means that the TAC should be divided equally over $n^*_{LC1} \leq \overline{n}_{LC1}$ vessels (see [18]), and none to any other boats. If, however, $TAC > \overline{TAC}_{LC1}$, it is cost-minimizing to increase the quotas of boat type $LC1$ because, by definition, these boats have lower average costs than boats of other types $\left(\tilde{c}_{LC1} < \tilde{c}_{LC2}\right)$. Therefore, the quota of the $\overline{n}_{LC1}$ boats of type $LC1$ should be increased until a switching point e^{**}_{LC1}, which is implicitly defined by $\dfrac{v_{LC1} e^{**}_{LC1} + f_{LC1}}{q_{LC1} X^{\alpha_z} \left(e^{**}_{LC1}\right)^{\beta_{LC1}}} = \dfrac{\Omega_{LC2}}{X^{\alpha_{LC2}}}$; it is only profitable to use the first boat of type $LC2$ if imposing higher effort on all $\overline{n}_{LC1}$ boats of type $LC1$ results in average costs higher than the minimum average costs of type LC2. In practice, that point may never be reached because there is a maximum limit on effort that can be exercised per boat given by e^{MAX}_{LC1} (if only because a year has 365 days). Hence, the manager should not use boats of type $LC2$ if $TAC \le \widehat{TAC}_{LC1}$ where $\widehat{TAC}_{LC1}$ is defined by the maximum harvesting level achieved by $\bar{n}_{LC1}$ boats of type $LC1$ running at a scale equal to $\hat{e}_{LC1} = \min\left\{e_{LC1}^{MAX}, e_{LC1}^{**}\right\}$. If $\overline{TAC}_{LC1} \le TAC \le \widehat{TAC}_{LC1}$, only boats of type $LC1$ are used at a scale equal to $\hat{\hat{e}} = \left(\frac{TAC}{\bar{n}_{LC1} q_{LC1} X^{\alpha_{LC1}}}\right)^{\frac{1}{\beta_{LC1}}}$. If $TAC > \widehat{TAC}_{LC1}$, boats of fleet type $z = LC2$ will also be used. As long as $n_{LC2}^{*} \le \bar{n}_{LC2}$, it is optimal to operate these vessels at their efficient scale (see [16]), and hence $n_{LC2}^{*} = \frac{TAC - \bar{n}_{LC1} q_{LC1} \left(X_{LC1}\right)^{\alpha_{LC1}} \left(\hat{e}_{LC1}\right)^{\beta_{LC1}}}{q_{LC2} \left(X_{LC2}\right)^{\alpha_{LC2}} \left(e_{LC2}^{*}\right)^{\beta_{LC2}}}$. If the TAC is even higher and all boats of the fleet type $z = LC2$ are in use, effort levels e_{LC1} and e_{LC2} should both be increased (if possible) until the average harvesting costs of boats of all three types $(LC1, LC2, LC3)$ are equal. We repeat these steps for all $z = LC3, \ldots, LCZ$. The total number of boats in the cod fishery are thus equal to

$$\sum_{z=1}^{Z} n_z(e, TAC, X) = \begin{cases} n_{LC1}^{*}(e_{LC1}^{*}) & \text{if} \quad TAC \le \overline{TAC}_{LC1} \\ \bar{n}_{LC1}(\hat{\hat{e}}_{LC1}) & \text{if} \quad \overline{TAC}_{LC1} \le TAC \le \widehat{TAC}_{LC1} \\ \bar{n}_{LC1}(\hat{e}_{LC1}) + n_{LC2}^{*}(\hat{e}_{LC1}, e_{LC2}^{*}) & \text{if} \quad \widehat{TAC}_{LC1} < TAC \le \widehat{TAC}_{LC1} + \overline{TAC}_{LC2} \\ & \quad etc. \end{cases} \qquad [23]$$

IV. An empirical application of the Northeast Arctic cod fishery

In this section we estimate the production and cost function from individual vessel data from the Directorate of Fisheries (Bergen, Norway). Next, since the NEA cod fishery is not a small scale fishery, its landings affect the price at which Norway exports cod – and hence also the landing prices. We empirically derive the percentage decrease in the landing price (or ex-vessel price) resulting from a one percent increase in the quantity of cod harvested – i.e., the inverse of the price elasticity of demand, sometimes also referred to as the price flexibility. Finally, we estimate the biological model for the NEA cod stock. All data sources are described in Appendix 3.

Estimating the production and the cost function

To estimate the cost and production functions of the various boat types, we use panel data from the period 1990-2000, which covers almost all ocean-going vessels that were active in the cod fishery in that time period. We have data on the quantity of cod harvested, days spent on catching cod and on the costs incurred per year for 107 trawlers, 25 factory trawlers, and 85 longliners. Most vessels have not reported for all of the 11 years; see Sandberg (2006) for more information on the data. Table 1 gives descriptive statistics of the data that will be used in the regression analysis.

	Days fishing cod 62°N	Days fishing in total	Days on sea	Cod harv. 62°N in tonnes	GRT	Total costs in NOK
Trawlers						
Mean	81.2	252.6	283.2	782	280.3	12 mln
Median	79.0	260.0	294.5	768	298.0	12 mln
Maximum	278.0	374.0	364.0	2882	499.0	32 mln
Minimum	2.0	42.0	112.0	3	33.0	0.52 mln
Std. Dev.	45.3	67.0	49.5	526	89.7	4.8 mln
Factory Trawlers						
Mean	50.5	181.5	181.5	1398	776.9	34 mln
Median	47.0	182.0	182.0	1303	660.0	34 mln
Maximum	122.0	299.0	299.0	4495	1428.0	57.7 mln
Minimum	8.0	37.0	37.0	150	473.0	15 mln
Std. Dev.	26.4	45.9	40.7	829	307.9	7 mln
Longliners						
Mean	46.5	218.0	310.7	306	216.2	12 mln
Median	43.0	217.0	318.0	291	202.0	11 mln
Maximum	134.0	342.0	356.0	874	688.0	28 mln
Minimum	10.0	106.0	207.0	109	100.0	2.6 mln
Std. Dev.	20.7	44.7	27.0	150	82.1	4.5 mln

Table 1. Descriptive statistics of the annual data used to estimate the cost and production function. The data covers the period from 1990-2000, and has been obtained from the Norwegian Directorate of Fisheries.

In economics, the relationship between inputs and output (the production function) is often inferred by estimating a cost function $C_z(X, TAC)$ using a flexible form. This approach is based on the assumption that whatever amount of fish a boat has caught, it has done so at minimum cost. In such a case duality applies (Varian, 1992, Chapter 6) and the production function can be inferred from the prices of the inputs and outputs. The advantages of this approach are that one does not need to assume a certain technological structure a priori (as we did in [11]) and also that it is statistically more efficient because the cost function and the first-order condition for cost minimization can be estimated jointly. In fisheries economics, this approach is less appealing because of several reasons. First of all, the standard cost function approach cannot be applied because one of the inputs in the production process, biomass, cannot be chosen freely by individual fishermen, and introducing quasi-fixed factors in the cost function typically complicates the estimation procedure considerably (Morrison, 1988; Morrison and Schwartz, 1996; van Soest et al., 2006). Second, fishermen are unlikely to always operate at minimum costs at all times. Markets are usually incomplete, fishermen face informational constraints, and payments of all inputs are not always determined by market prices directly because crew members may receive shares of the harvesting revenues rather than a fixed wage (McConnell and Price, 2006; Sandberg, 2006). Finally, it is not necessarily the case that all fishermen always try to maximize profits because other considerations (including status seeking) may also play a role (Gezelius, 2007; Ginkel, 2009; Holland, 2008; Poos, 2010; Salas and Gaertner, 2004). Because of these reasons it is preferred to estimate the technical relations [11] and [12] separately rather than using a cost function that assumes fishermen choices to be optimal (i.e. cost-minimizing). This is in line with Felthoven and Morrison Paul (2004) who argue that “fishing technology [should] be analyzed directly (through a “primal” approach), by focusing on inputs and outputs, rather than by modeling choices based on costs, profit, or market prices.” Therefore, we estimate the production function [11] and the input cost function [12] separately. As a robustness checks, we have estimated them jointly assuming duality to hold, but the results were judged to be inferior compared to the primal approach; see Appendix 2.

Estimating the production function of the three vessel types

First, we estimate the production function for each fleet type *z* given in [11]. Table 1 shows that the ocean-going cod fleet consists of three types: trawlers (47.8% of the boats), factory trawlers (18.5%), and longliners (33.7%). We denote these three boats types by $z = T$, $z = FT$, and $z = LL$, respectively. In our model, effort e_{izt} is defined as the number of days a boat is fishing cod north of 62 degrees latitude, multiplied by its size (GRT). Including the size of the boat takes differences in operational intensity into account (Asche et al., 2009). We cannot rule out an omitted variable bias – caused for example by differences in the skillfulness of individual skippers (Sandberg, 2006; Squires and Kirkley, 1999). This poses a particular problem if the "skipper effect" is positively correlated with the size of the boat, which may be the case if the best skippers run the largest boats. Therefore, we estimate the model by means of Ordinary Least Squares (OLS) with fixed effects on the cross-sections (that is, we use vessel-specific fixed effects). As our number of cross-sections is much larger than the number of years, we use a robust variance-covariance matrix that produces panel corrected standard errors (PCSE), as proposed by Beck and Katz (1995). We estimate [11] for each boat type separately, thus allowing all parameters to be vessel type specific:

$$\log(h_{izt}) = \log(q_z) + \alpha_z \log(X_t) + \beta_z \log(e_{izt}) + \upsilon_{iz} + \varepsilon_{izt}, \qquad [24]$$

where ε_{izt} is an error term, while υ_{iz} is the estimate of the fixed effects. The latter sum up to zero when aggregating over all boats of type *z*, and hence υ_{iz} can be interpreted as individual deviations from the average catchability coefficient $\log(q_z)$. The regression results are presented in Table 2. The stock-output elasticity α_z is estimated to be 0.58 for trawlers, 0.38 for factory trawlers, and 0.22 for longliners. The effort-output elasticity β_z is estimated to be 0.85 for trawlers, 0.89 for factory trawlers, and 0.92 for longliners. These coefficients are similar to the ones found by Kronbak (2004).[4]

	Trawlers	Factory Trawlers	Longliners
α: stock-output-elasticity	0.58 (0.08)	0.38 (0.11)	0.22 (0.09)
β: effort-output elasticity	0.85 (0.05)	0.89 (0.06)	0.92 (0.08)
log(q)	-7.39 (1.56)	-3.29 (2.31)	-0.54 (1.88)
Durbin Watson	1.72	1.55	1.52
Adjusted R^2	0.93	0.76	0.93
Total observations	348	157	226
Number of boats	84	22	64

Table 2. Regression output for the production functions of the three vessel types. The standard errors are presented in parentheses.

Estimating the cost function of the three vessel types

We estimate the fixed and variable costs of harvesting cod (as specified by [12]) as follows. The available cost data for each vessel contains expenses made for fuel, salt and packing, social costs, wages, vessel insurance, other insurance, vessel maintenance, gear and equipment maintenance, provisions, vessel depreciation, and a category “other costs”. In total, there are 11 cost components, which are indexed $k = 1 \ldots 11$. Total costs incurred by vessel i of type z in year t are given by the vector of nominal cost components, C_{izkt} which are subsequently corrected for

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[4] Eide et al. (2003), however, find an effort-output elasticity of larger than one, which is unexpected for a demersal fish stock. This result may be explained by the fact that they use daily data, where effort is given by hours of trawling – diseconomies of scale do not necessarily materialize at the very short term.

inflation using the Producer Price Index PPI_t. We calculate the part of the total costs incurred for catching cod by the share of days vessel *i* spends on catching cod in the total number of days vessel *i* is fishing at sea. Using index *j* to enumerate these nine fish species (with cod being *j* = 9) and using D_{izjt} to denote the number of days in year *t* that vessel i of type z catches species *j*, the costs attributed to catching cod by a vessel *i* of type *z* in year *t* are

$$c_{izt} = \frac{D_{iz9t}\sum_{k=1}^{11} c_{izkt}}{PPI_t \sum_{j=1}^{9} D_{izjt}}. \qquad [25]$$

To estimate [12], we use [25] as the dependent variable and regress it on an intercept as well as on the number of tonnage-days vessel *i* spent harvesting cod in year *t*. As before, we use fixed effects and panel corrected standard errors to estimate

$$c_{izt} = a_{0z} + a_{1z}e_{izt} + a_{2zi} + \varepsilon_{izt}, \qquad [26]$$

where the intercept a_{0z} equals the fixed costs per boat operating in the cod fishery (f_z), while a_{1z} reflect variable costs per tonnage-day spent fishing cod (v_z). The coefficient for the fixed effects a_{2zi} can be interpreted as individual deviations from a_{0z}. Table 3 shows the estimation results.

	Trawlers	Factory Trawlers	Longliners
Fixed adjustment costs in million NOK	1.55 (0.21)	2.89 (0.74)	0.28 (0.15)
Variable costs per tonnage-day in NOK	131.66 (8.55)	218.49 (17.98)	239.38 (15.21)
Durbin Watson	1.36	1.25	2.24
Adjusted R^2	0.84	0.78	0.77
Total observations	348	157	226
Number of boats	84	22	64

Table 3. Regression output for the cost functions of the three vessel types. The standard errors are presented in parentheses.

The variable costs for one day of fishing cod are 36,960 Norwegian Kroner (NOK) per trawler (of average size 280 GRT), 169,386 NOK per factory trawler (of size 777 GRT), and 51,863

NOK per longliner (of size 216 GRT). The fixed costs per year are 1.55 million NOK per trawler, 2.89 million NOK per factory trawler, and 0.275 million NOK per longliner. We have performed robustness checks to validate our results by splitting the total costs into variable and fixed costs in an ad hoc way and compared them with our findings here; see Appendix 2.

The inverse price elasticity of Northeast Arctic cod

Estimating the inverse demand function for cod (see [2]) is complicated, because the price and quantity data are *equilibrium* outcomes of market interactions, and hence are the result of both demand and supply. In particular there may still be supply effects if (i) the manager decides on the TAC in an ad hoc manner and may set higher quotas when world prices are high, (ii) there is a tendency to harvest illegally when prices are high, or (iii) the quotas are not fully exercised when prices are really low. Because of these reasons we use Two Stage Least Squares (2SLS), instrumenting for landings in the first stage of 2SLS using biomass levels of the past two years as instruments.

We estimate the inverse elasticity of demand – the price flexibility – using export-prices. In the NEA-cod fishery, ex-vessel prices and export prices are co-integrated (Asche et al., 2002), and therefore one can use the price flexibility to construct a demand function for the ex-vessel fish market. While in our theoretical model we assume the demand function for cod to be linear, econometrically it is preferred to estimate the demand function using a log-linear specification. Hence, our regression model is

$$\log(P_t) = a_{21} + a_{22}\log(H_t) + a_{23}\log(\mathrm{Inc}_t) + a_{24}\log(\mathrm{S}_t), \qquad [27]$$

where P_t is the deflated price of cod (in NOK), H_t are the total landings of the whole stock of NEA cod, Inc_t is disposable income (given by real GDP in Europe), and S_t is the price of a substitute product (saithe *(Pollachius virens)*).[5] The time series for landings and biomass suffer from autocorrelation. We therefore, estimate [27] as an ARMA(1,1) process. Following Fair (1984), the lagged values of P_t and H_t will added to the list of instruments; see also Pindyck and Rubinfeld (1991). We obtain the following estimates:

$$\begin{array}{llllll}\log(P_t) = & -21.87 & -0.50\log(H_t) & +1.95\log(\mathrm{Inc}_t) & +0.50\log(S_t) & +u_t, \\ \text{s.e.} & (5.41) & (0.1) & (0.35) & (0.12) & \end{array}$$

$$\begin{array}{llll}u_t = & -0.31u_{t-1} & +0.80\varepsilon_{t-1} & +\varepsilon_t, \\ \text{s.e.} & (0.62) & (0.91) & \end{array}$$

with an adjusted R² of 0.97 and a Durbin-Watson (DW) statistic of 1.27. We find that the inverse price elasticity is 0.5, i.e. if the supply of cod increases by 1%, the world price drops by 0.5%. The Durbin-Watson statistic suggests that we may not have fully succeeded in solving the issue of autocorrelation. As a further robustness check we have estimated the same model in different specifications (see Appendix 2). These additional estimations support an inverse price elasticity of around 0.5. From [2], the inverse price elasticity is given by $(H/P)(dP/dH) = -bH_t/P_t$, which should equal 0.5. Using the inflation-corrected average price per kilogram of cod between 1997 and 2007 of 12.59 NOK, and the annual average landing of cod of 527,815 tonnes, we find $b = 1.19 \cdot 10^{-8}$. Substituting this value of *b*, together with the price and quantity data, into [2], we find $a = 18.88$.[6] Hence, the price of a kilogram of cod is given in our model as:

$$P_t = 18.88 - 1.19 \cdot 10^{-8} H_t. \qquad [28]$$

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[5] Due to constraints in the fishing process, it seems unlikely that fishermen can substitute saithe for cod – at least not in the same way consumers do. If they could, using saithe in the demand function would be problematic (as it may measure a supply effect). The size of the coefficient and robustness checks in the Appendix suggests that this is not a serious problem.

[6] Using not average prices and landings, but the price in a specific year gives slightly different values for a and b around our estimate. If one is particularly interested in a specific year, it would obviously be better to use these year-specific estimates.

The biological model

We use a discrete version of the biological model (see [4] and [5]) to estimate the population growth function for the NEA cod:

$$X_t - X_{t-1} + H_t = a_0 X_{t-1} + a_0 b_0 X_{t-1}^2 + \varepsilon_t, \qquad [29]$$

where the error term ε_t is expected to follow an autoregressive (AR) process. Here, a_0 yields the point estimate for the intrinsic population growth rate *r*, and b_0 is our point estimate for $1/K$. Concerning serial correlation, three different models are considered: model M1 is estimated without an AR term, M2 is estimated as an AR(1) process, and M3 is estimated as an AR(2) process. The results are presented in Table 4. The model with the lowest AIC gives a carrying capacity (K) of 5.41 million tonnes and an intrinsic growth rate (r) of 0.55. These estimates are similar to the results obtained by Kugarajh et al. (2006). Hence, [5] reads as $G(X) = 0.55X\left(1 - \frac{X}{5.41}\right)$. The total biomass that supports a maximum sustainable yield (MSY) thus equals $5.41/2 = 2.7$ million tonnes of cod, and the associated MSY is equal to 743,000 tonnes.

Model	M1	M2	M3
r	0.54 (0.06)	0.55 (0.09)	0.56 (0.08)
K^{-1} (in 10^{-7} tonnes)	1.78 (0.2)	1.85 (0.34)	1.87 (0.31)
AR(1)		0.25 (0.15)	0.31 (0.14)
AR(2)			-0.18 (0.14)
Durbin Watson	1.50	1.89	2.02
Adjusted R^2	0.01	0.03	0.05
AIC	28.39	28.37	28.38
Total observations	61	60	59

Table 4. Regression output for the biological model. The standard errors are presented in parentheses. The data covers the period 1946-2007.

V. Using the empirical results for an optimal policy

We can now use the estimates obtained in section 4 to derive the optimal quota sizes per vessel of each type, the optimal amount of biomass, and the associated economic rents as indicated in section 3. We start by calculating the optimal scale of operation (as measured in tonnage-days) for each of the three vessel types (see [16]), and also the optimal number of fishing days (by dividing [16] by the average GRT of the boat type). We find that the optimal number of days fishing cod for the three boat types varies between 62 for longliners and 238 for trawlers; see Table 5. This is more than the time the boats spend currently catching cod (see Table 1) – consistent with intuition because the current situation is most likely characterized by overcapacity.

	Trawlers	Longliners	Factory Trawlers
Optimal tonnage days	667122	134514	1070196
Optimal days	238	62	138

Table 5. Optimal number of days fishing cod for different boat types, as measured by days and tonnage days.

We now turn to the question how to set an optimal TAC. First, we present results for the situation where the fleet composition is flexible, and without an upper limit on the number of boats that can be used. We start by calculating the average costs of harvesting one kilogram of cod for each of the three vessel types, as given by [20]. At a given level of remaining biomass equal to *X*, the costs equal $C_T = 1{,}327{,}706 / X^{0.58}$ for trawlers, $C_L = 955 / X^{0.22}$ for longliners, and $C_{FT} = 23{,}557 / X^{0.38}$ for factory trawlers. Multiplying these numbers by TAC_z gives the total costs of all boats belonging to one fleet type; see [19]. Furthermore, we find that trawlers have always lower average harvesting costs than factory trawlers (when both are operating at their efficient scales), for all levels of biomass between 0 and *K*.[7] Similarly, trawlers have lower average harvesting costs than longliners, as long as biomass is 530,000 tonnes or higher. In the analysis that follows, it is shown that if biomass is below this level, it will be desirable to stop fishing altogether. Therefore, we can conclude that – if fishing takes place – trawlers are always the cost-minimizing option; $LC1 = T$.

Next, we use our model to determine the optimal long run equilibrium values for biomass, TAC, and fleet profits for the various management objectives; see Table 6. Three scenarios will be compared. First, the government minimizes fleet costs and allocates all quotas to trawlers (potentially through an ITQ mechanism). Second, the government not only cares about economic rents but pursues environmental objectives too. In this scenario the government therefore only allows longliners to enter the cod fishery, as they are more environmentally-friendly than trawlers. Third, we solve for the case where the government also has other objectives (like cultural and social considerations), embodied by assuming that society prefers a diverse fleet as it is today.[8]

The results are presented in Table 6. First, we find that discounting has a negligible impact on optimal long run policies – the optimal biomass levels for a discount rate of zero percent are less than two percent smaller than for a discount rate of ten percent. Second, independent of the fleet composition, we find that the optimal biomass is always larger than the MSY stock of 2.7

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[7] In our analysis we ignore the fact that factory trawlers create added value by processing the fish on board. That means that our regression results underestimate the benefits (or overestimated the costs) from using factory trawlers that produce frozen fish fillet rather than raw fish. Therefore, it seems unfair to compare them with the other boats. Hence, factory trawlers will be omitted from the rest of the analysis, except in the scenario where a diverse fleet is preferred by society.

[8] Since our dataset comprises almost all ocean-going vessels that are engaged in the cod fishery, we derive the parameters from our dataset. That is $\theta_T = 0.478$, $\theta_{FT} = 0.185$, $\theta_{LL} = 0.337$.

million tonnes of cod. Hence, search costs and market power outweigh the impact of discounting (even when using a discount rate of 10%), as the optimum is always on the right hand side of the logistic growth function. Third, we find that the optimal biomass is smallest in the case fleet profits are maximized and the cheapest boats – trawlers – are used (and hence the amount of cod caught is largest). And the remaining biomass is largest in case of environmental concerns, when the government only allows cod harvesting to take place by longliners.[9] Our results are similar to results obtained for the same cod stock by Armstrong (1999), who found a TAC of 650,000 tonnes to be optimal and Armstrong and Sumaila (2000) who found an optimal TAC of 450,000 tonnes.

Management objective	Discount rate	Biomass (mln tonnes)	Harvests (mln tonnes)	Profits (bln NOK)
Maximizing rents	0%	3.94	0.59	4.86
Environmental concerns	0%	4.35	0.47	2.84
Fleet diversity	0%	4.12	0.54	3.97
Maximizing rents	10%	3.89	0.60	4.86
Environmental concerns	10%	4.34	0.47	2.84
Fleet diversity	10%	4.09	0.55	3.96

Table 6. Optimal steady-state biomass and harvest levels for several harvesting scenarios for maximizing rents (using only trawlers), environmental concerns (using only longliners), and cultural diversity (using trawlers, factory trawlers, and longliners).

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[9] Recall that we assume the government to maximize economic profits (with or without constraints on the type of boats used) because more than 90% of NEA cod is exported. If the government not only cares about economic profits but also about consumer surplus (and hence aims to maximize social welfare as the sum of consumer surplus and economic profits, the optimal steady-state biomass is 3.14 mln tonnes with an associated TAC of 0.72 mln tonnes (trawlers), 3.33 mln and 0.70 mln tonnes (longliners), and 3.20 and 0.72 mln tonnes (mixed fleet). For the HCR, we find that maximizing profits leads to somewhat smoother harvesting activity than maximizing the sum of profits and consumer surplus (as harvesting is continued at lower biomass levels, but not as aggressive at higher biomass levels). Then, the minimum biomass levels would be around 1.5 million tonnes.

So we find that the optimal biomass levels are much higher than the biomass levels that we are currently experiencing; see Figure 1. This raises the question how the optimal transition path looks like – as given by the HCR [10]; see Figure 2.

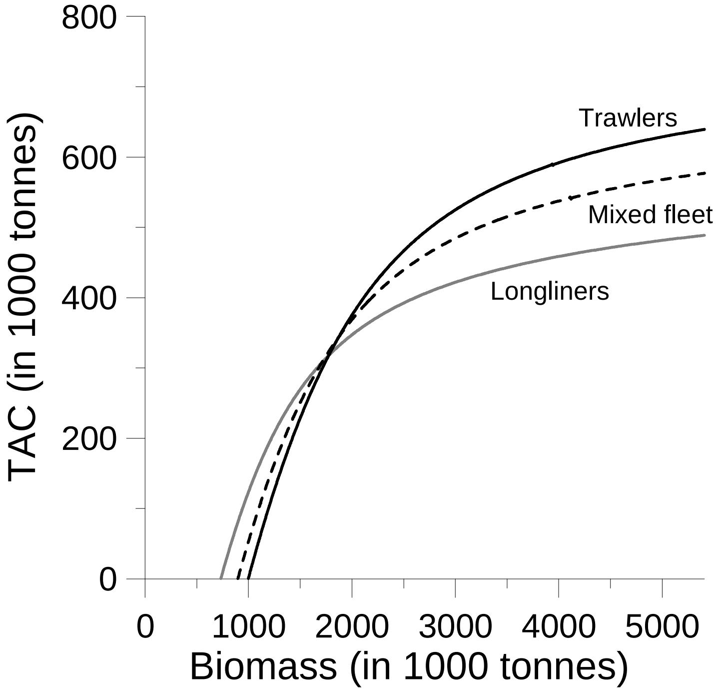

Figure 2. The derived TAC (total allowable catch) as a function of total biomass given by the optimal harvest control rule for using only trawlers, longliners, or a mixed fleet.

First, we find that the optimal HCR is concave: a one percent decrease in the remaining biomass calls for a more than proportional decrease in the quantity harvested. Second, we find that the minimum biomass level, below which all fishing activities should be ceased, is higher for trawlers than for longliners – as trawlers are getting relative inefficient at low biomass levels (see the stock-output elasticity in Table 2). Third, we find that at higher biomass levels, it would be optimal to harvest more with a fleet of trawlers compared to longliners. Fourth, we find that just allowing longliners to enter the fishery is quite expensive as the annual profits are 2 bln NOK smaller than in case the fishery is managed to maximize rents, and allowing for a diverse fleet reduces profits by 0.9 bln NOK. Hence, the manager needs to decide whether the benefits of pursuing environmental objectives or cultural objectives exceed these costs.

The minimum biomass levels we find are similar to the ones found by Arnason et al. (2004), who start fishing at 1.3 million tonnes of biomass, and Kugarajh et al. (2006) who found it optimal to start fishing at around one million tonnes of biomass. In these studies, harvesting was never higher than around 500,000 tonnes (Arnason et al., 2004) and 750,000 tonnes (Kugarajh et al., 2006).

If the situation is characterized by fleet lock-in, it is not necessarily possible to follow the cost-minimizing policy identified in Table 6. If the optimal TAC of 590,000 tonnes needs to be harvested using trawlers operating at their efficient scale, 206 vessels are needed. Let us analyze how to allocate the TAC in the most efficient situation if the fleet comprise of only 90 trawlers and a large number of longliners.[10] Plugging in all estimated parameters into [20] we find that it is cheapest to let trawlers operate 365 days a year, before using longliners if biomass levels are above 600,000 tonnes (cf. [23]). Therefore, if the manager aims to maximize the rents from cod harvesting, she should force all 90 trawlers to operate the whole year. In addition, it is then optimal to also have 97 longliners active in the cod fishing industry, each of which operates at its efficient scale (see the third line in equation [23] and Table 7). Surprisingly, the optimal amount of biomass is then larger than when using just trawlers or longliners (and hence the TAC is smaller, given that the optimal biomass lies on the right hand side of the logistic growth curve); compare Tables 6 and 7. The explanation for this counter-intuitive finding is that using additional longliners will negatively affect the efficiency of trawlers through the stock effect. At lower

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[10] This example is somewhat stylized, since in reality the TAC is also caught by international vessels that are not part of the Norwegian fleet.

biomass levels, trawlers are getting less efficient than longliners (see the estimates of the stock-output elasticities (α_z) presented in Table 2, and [9]). This indirect cost explains why it is optimal to use less longliners – given that the trawler fleet is already operating at maximum capacity.

Discount rate	Biomass (mln tonnes)	Harvests (mln tonnes)	Profits (bln NOK)	# Trawlers (number of vessels)	# Longliners (number of vessels)
0%	4.42	0.44	4.34	90	97
10%	4.40	0.44	4.34	90	119

Table 7. Optimal steady state biomass and harvest levels for the case of cost-minimization harvesting if the fleet is characterized by a lock-in.

VI. Discussion and conclusions

In this paper we developed a management plan to determine the optimal steady-state biomass, TAC, and the associated economic rents for three different management objectives for the NEA cod fishery. Our model allows the decision maker to determine the optimal allocation of a TAC over the various types of vessels currently used in the fishery (trawlers, longliners and factory trawlers). Having derived the associated cost functions of catching cod, the information can subsequently be used to determine the optimal steady state level of biomass, as well as the harvesting trajectory towards it (the so-called HCR). All equations of the model have been estimated using detailed data of the NEA cod fishery, while addressing the many statistical difficulties associated with them.

Our analysis shows that fleet structure is important for optimal policy as it determines not only how many boats optimally harvest a given TAC, but also the size of the overall TAC and the associated optimal biomass levels. Taking the cost structure of the industry into account affects the optimal biomass levels substantially, as the steady-state stock is 3.94 million tonnes in the case the government aims to maximize long-run financial welfare (implying that the fishing fleet should consist of trawlers only, because they are most efficient in harvesting) while it is 4.35 million tonnes if the government aims to maximize long-run profit while limiting the fleet structure to consist of longliners only – as they are indicated to impose least damages to the marine ecosystem. These results can be used by the decision maker to decide how to set an optimal TAC, to choose which vessels are allowed to participate in the fishery, and assess the costs of deviating from the least-cost approach.

Some model assumptions deserve special attention, as they may have potential policy implications. First, we assume cod growth to be represented by a simple logistic growth model. Adding more biological realism may alter our results; see Eikeset et al. (2010a) for a study that uses a more complex biological model to determine optimal HCRs. While the way in which the cost structure of different vessel types affect the management plan would carry over to a more complex biological model, the specific optima – such as the size of optimal biomass or the TAC – will probably be different. Second, we focus our analysis on cod harvesting ignoring all economic and ecological interactions with other fish species (Nøstbakken, 2006; Salvanes and Squires, 1995; Squires et al., 1998). An interesting further avenue would be to investigate how the economies of scale that we identified in this paper relate to economics of scope (i.e. the possibility to catch other fish species). Third, we assume that each fleet can be represented by a typical boat. In reality, a fleet comprises many boats that differ in age, size, productivity, and costs. This is not accounted for in our model, giving rise to inefficiencies when quotas are distributed over boats. These inefficiencies could be eliminated by an ITQ mechanism (within the fleet constraints that we have outlined), even though the costs and disadvantages of such a mechanism can easily outweigh the potential benefits (Sumaila, 2010). Fourth, while our results give optimal quotas in tonnage-days, in practice it would be desirable to hand out the actual quotas – transferable or not – as catch shares to remove the incentive to substitute controlled for uncontrolled capital. Finally, analyzing the cost of building up and maintaining fishing capacity was beyond the scope of this paper, but would be worth exploring.

The study presented here is novel, as it provides an optimal management plan that is flexible and can be adapted to various policy objectives concerning the utilization of the fleet going beyond cost-minimization. However, it can only be considered as a first step towards optimal management of natural resources that recognizes the full array of preferences society holds regarding how these resources should be exploited.

Appendix 1: Deriving an analytical harvest control rule

Deriving an harvest control rule (HCR) is fairly straightforward if the discount rate is assumed to be equal to 0 $(\delta = 0)$; see Sandal and Steinshamn (1997a; 2001). The current-value Hamiltonian of the optimal control problem in section 3 can be written in general terms as follows:

$$\mathcal{H} = \Pi\left(X, TAC\right) + \varphi\left(G(X) - TAC\right), \tag{A1}$$

and the associated first-order conditions are

$$\mathcal{H}_{TAC} = 0 \quad \Rightarrow \quad \varphi = \Pi_{TAC}(X, TAC), \tag{A2}$$

$$\dot{\varphi} = \delta\varphi - \mathcal{H}_X \quad \Rightarrow \dot{\varphi} = -\Pi_X\left(X, TAC\right) + \varphi\left(\delta - G_X\left(X\right)\right), \tag{A3}$$

$$\dot{X} = \mathcal{H}_{\varphi}. \tag{A4}$$

We aim to derive the optimal HCR which is, by definition, a function of the stock of biomass, *TAC*(*X*). Substituting this generic expression of the HCR into [A1] and taking the first derivative with respect to time, we have

$$\dot{\mathcal{H}} = \left(\frac{\partial \mathcal{H}}{\partial X} + \frac{\partial \mathcal{H}}{\partial TAC} \frac{dTAC}{dX} \right) \dot{X} + \mathcal{H}_{\varphi} \dot{\varphi} = \delta \varphi \dot{X} \qquad [A5]$$

where the latter equality holds because of [A2] and [A3]; see also Sandal and Steinsham (2001). That means that the Hamiltonian is constant over time if $\delta = 0$. In that case, maximizing the Hamiltonian then boils down to just choosing *X* to maximize the instantaneous profit flow in steady state (Sandal and Steinshamn, 2001):

$$\mathcal{H} = \max_{X} \Pi \big|_{TAC=G(X)} = \Pi^{*}(X) \qquad [A6]$$

Substituting [A6] and [A2] into [A1], we obtain the following equality:

$$\Pi^{*}(X) = \Pi(X, TAC) + \Pi_{TAC}(X, TAC)\left[G(X) - TAC\right]. \qquad [A7]$$

Using the instantaneous profit function [1], the growth function [5] and [A7], we find the optimal harvest control rule as presented in [10].

Appendix 2: Model validations

Model validation of the production and cost functions

As a robustness check, we have split total costs into variable and fixed costs, by assuming that variable costs contain expenses made for fuel, salt and packing, social costs, provisions, wages, and a category “other costs”. We found that the average cost per trawler fishing cod is 36,823 NOK, per factory trawler 158,452 NOK, and per longliner 47,285 NOK. The fixed costs that are assumed to comprise vessel insurance, other insurance, vessel maintenance, gear and equipment maintenance, and vessel depreciation are 1.6 million NOK for trawlers, 3.57 million NOK per factory trawler, and 0.75 million NOK per longliner. These estimates are comparable to what has been estimated in our regression analysis, even though the fixed costs in the regression analysis are somewhat lower, especially for longliners. This may be due to the fact that some costs were assumed to be fixed (e.g. maintenance), but in reality those costs are partially dependent on effort. Since our regression analysis is able to capture this effect, while the ad hoc composition here is not, one would indeed expect the ad-hoc composition to provide lower cost estimates.

As a further robustness check we have estimated the relationship of costs and harvests jointly without using effort as a variable, by combining [24] and [26]. The model $\log\left(TC_{it}\right)=\log(a_0)+a_1\log(X_t)+a_2\log(h_{it})+\upsilon_{iz}+\varepsilon_{it}$ [A8]

is again estimated with fixed effects. The results are presented in Table A1.

	Trawlers	Factory Trawlers	Longliners
a_0	13.67 (1.04)	12.75 (1.83)	8.92 (1.37)
a_1	-0.44 (0.06)	-0.39 (0.08)	-0.21 (0.06)
a_2	0.81 (0.03)	0.82 (0.05)	0.81 (0.05)
Durbin Watson	2.26	1.64	2.64
Adjusted R^2	0.97	0.83	0.79
Total observations	437	169	309
Number of boats	107	25	85

Table A1. The coefficients of model [A8], estimating the relationship between costs, total biomass and harvests.

We find a stock-output elasticity smaller than one and an effort-output elasticity smaller than zero, which is consistent with our earlier findings. In order to judge the quality of each model, we will assess their forecasting ability. Table A2 shows the forecasting ability of the production functions [24] and cost functions that are estimate directly [26] compared with the model [A8]. All models have been estimated in the period 1990-1995, while the period 1996-2000 has been forecasted. The bias proportion indicates how the mean of the predicted time series differs from the original one, while the variance proportion tells us how the variance of the two series differs. We find that the models [24], and [26] perform better than model [A8], indicated by the lower bias and variance proportion and consequently the higher covariance proportion.

	Trawlers			Longliners			Factory Trawlers		
Model	Production	Cost	Jointly	Production	Cost	Jointly	Production	Cost	Jointly
Equation	[24]	[26]	[A8]	[24]	[26]	[A8]	[24]	[26]	[A8]
Bias proportion	0.344	0.258	0.078	0.36	0.089	0.52	0.455	0.248	0.476
Variance proportion	0.013	0.019	0.32	0.12	0.026	0.059	0.012	0.006	0.02
Covariance Proportion	0.643	0.723	0.602	0.52	0.885	0.421	0.533	0.746	0.504

Table A2. The forecast ability of models [24] and [26] estimated directly and model [A8] estimated indirectly.

Model validations of demand function

We have estimated the inverse price elasticity under various different specifications to evaluate the robustness of our results. First, we have estimated [27] integrated of order one without ARMA terms. This delivers a slightly lower inverse price elasticity of -0.40 as given by

$$\begin{array}{l}\Delta\log\left(P_t\right)=0.0-0.40\Delta\log\left(H_t\right)+1.72\Delta\log\left(\text{Inc}_t\right)+0.62\Delta\log\left(S_t\right)+\varepsilon_t\\ \text{s.e.}\qquad\quad (0.06)(0.14)\qquad\qquad (2.34)\qquad\qquad\quad (0.15),\end{array}$$

with an adj. R²=0.36 and DW=1.92. Instruments for $\Delta\log\left(H_t\right)$ are $\Delta\log\left(B_{t-1}\right),\Delta\log\left(B_{t-2}\right)$.

Furthermore, the same model has been estimated without income as a variable, giving an elasticity of -0.42 and the following results:

$$\begin{array}{l}\Delta\log\left(P_t\right)=0.03-0.42\Delta\log\left(H_t\right)+0.59\Delta\log\left(S_t\right)+\varepsilon_t\\ \text{s.e.}\qquad\quad (0.03)\ (0.13)\qquad\qquad (0.15),\end{array}$$

with an adj. R²=0.36 and DW=1.89. Instruments for $\Delta\log\left(H_t\right)$ are $\Delta\log\left(B_{t-1}\right),\Delta\log\left(B_{t-2}\right)$.

Omitting the price for saithe gives the same results:

$$\Delta\log\left(P_t\right) = 0.08 - 0.42\Delta\log\left(H_t\right) + \varepsilon_t$$
$$\text{s.e.} \qquad (0.03) \ (0.17),$$

with an adj. R²=-0.02 and DW=1.62. Instruments for $\Delta\log\left(H_t\right)$ are $\Delta\log\left(B_{t-1}\right), \Delta\log\left(B_{t-2}\right)$.

Alternatively, we have re-estimated model [27] without landing as independent variable, but with export quantity directly.

$$\log\left(P_t\right) = -19.33 - 0.61\log\left(Q_t\right) + 1.76\log\left(\mathrm{Inc}_t\right) + 0.73\log\left(\mathrm{S}_t\right) + u_t$$
$$\text{s.e.} \qquad (3.29) \ (0.07) \qquad (0.22) \qquad (0.09),$$

$$u_t = -0.16u_{t-1} + 0.09\varepsilon_{t-1} + \varepsilon_t$$
$$\text{s.e.} \quad (1.53) \quad (1.50)$$

with an adjusted R²=0.98, DW= 1.90. Instruments for $\log\left(Q_t\right)$ are $\log\left(B_{t-1}\right), \log\left(B_{t-2}\right)$.

The estimated elasticity is a bit higher now (0.61), which is not unexpected, because exports quantities have a much more direct impact on prices than landings. All in all, we can conclude that the estimated inverse price elasticity of -0.50 seems reasonable.

Appendix 3: Data sources

Equations [24]-[26]: Data for harvests, costs and effort has been obtained by the Directories of Fisheries, Bergen, while biomass comes from ICES (2009). The cost data has been deflated with the Producer Price index for Norway taking from the OECD, (2008) using the year 2000 as a benchmark. The OECD data has been accessed via www.SourceOECD.org/database/OECDStat.

Equation [27]- [29] and Figure 1: Landings and biomass are taken from ICES (2009). Export prices for cod and saithe are inferred from export values and export quantities; see Timmer and Richter (2009) for more information on the method. For each export commodity i (“Atlantic cod, fresh or chilled”, “Atlantic cod, frozen”, “Atlantic cod, salted, or in brine”, “Cod, dried, unsalted”, “Cod, salted, and dried” a price is calculated by dividing the total value in a given year by the total quantity: $P_{it} = V_{it} / Q_{it}$. A weighted export price is obtained by multiplying each price by its value and dividing it by the value of all exports given by $P_t = \sum_{i=1}^{5} P_{it} V_{it} / \sum_{i=1}^{5} V_{it}$. The data for saithe is given by "Saithe, dried, salted or in brine". This data was accessed with Fish Stat Plus (FAO, data from "FAO Yearbook of Fishery Statistics – Commodities"; the data was collected originally by Statistics Norway). These is annual data for the period 1976-2006. European income is proxied by real European GDP (Maddison, 2010). The data has been corrected for inflation, and has been converted from US Dollar into Norwegian Kroner using exchange rates from the OECD (2010). The KG price for cod is given by the off-boat sales prices ("Førstehåndspris") as given by the Directories of Fisheries, Bergen (Fiskedirektoratet, 2007). To make the price data comparable with the costs data we have used, again, the producer price index from the OECD. The baseline year was as before 2000. The average KG price is the average price between 1997 and 2007.

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