

HARVEST AND INVESTMENT DECISIONS UNDER ANNUAL AND MULTIANNUAL ADJUSTMENT OF FISH QUOTA

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ABSTRACT

Yearly revisions of Total Allowable Catch under EU policies for the management of North Sea fisheries come at high management costs and capital adjustment costs. It is unclear whether current EU fisheries policy strikes the right balance between the need to regularly adjust fish quota to new information on one hand, and the costs of gathering information and adjusting fisheries capital stock on the other hand. To analyze this question we present a model for a single-species fishery, where a profit maximizing decision-maker jointly determines optimal harvest and capital adjustment levels. Two alternative management systems are compared to the case of sole ownership without policy constraints: annual constrained quota adjustment and multiannual quota adjustment. In the case of unconstrained sole ownership the decision maker optimizes harvest and capital adjustment levels, while under annual constrained quota adjustment change in harvest is constrained by the harvest level of the previous year. Under multiannual quota adjustment capital adjustment is optimized on an annual basis while harvest is fixed for a longer period. We analyse quota adjustment in a stochastic setting, and compare results for the total discounted net benefits that include management costs and fishermen's capital adjustment costs. For the purpose of illustration we apply the model to North Sea plaice. Results of annual constrained quota adjustment show that as the system becomes more rigid the optimal harvest policy changes less between different levels of previous harvest. Consequently, as harvest in the previous period increases fewer investments are required. Results of multiannual quota adjustment show that both optimal policies change very little as the frequency of harvest change decreases. The change in optimal policies, however, decreases together with decreasing frequency of harvest change.

Keywords: stochastic fish growth, stochastic dynamic programming, capital adjustment, Total Allowable Catch, North Sea plaice

INTRODUCTION

Irreversibility of fisheries capital stock leads to serious problems for fishermen and policy makers. Total Allowable Catch (TAC) of North Sea fish species such as plaice and sole are established on an annual basis as new catch and biological survey data become available. Yearly TAC updates, however, come at high management costs and high capital adjustment costs. When TACs are re-established, researchers, policy makers and stakeholder organisations gather to discuss the new figures, which induce management costs. Furthermore, fishermen's capital investments have a long time horizon as fishing vessels can last up to thirty years. Adjusting the fisheries capital stock, or leaving the existing capacity idle, is therefore expensive and is often considered irreversible.

With the industrialization of fisheries and the consequential problem of over-fishing the impact of capital adjustment and irreversible investment have become important issues in fisheries economics (Clark et al., 1979; Eisenack et al., 2006). It is increasingly becoming apparent that fishery management may fail if the financial aspects and consequences are not analyzed (Bulte and Pennings, 1997). Early studies that include capital adjustment and irreversible investment in the optimization of fishery policy have focused on the effects of linear investment costs (Clark et al., 1979; Charles, 1983; McKelvey, 1983, 1985) and non-linear investment costs (McKelvey, 1983; Boyce, 1995). Different assumptions have led to various results for the optimal path of capital adjustment. Clark et al. (1979) and McKelvey (1985) find an optimal initial jump in capital investment, followed by a period of capital and fish stock depreciation. Also Boyce (1995) observes that capital adjustment is characterized by an initial period of continuous growth of fleet size. Charles (1983) on the other hand proves that the optimal capital capacity is subject to fluctuations. A more detailed overview of these studies is provided in Eisenack et al. (2006). Recent

studies have been conducted by Eisenack et al. (2006) and by Singh et al. (2006). Where in early approaches the capital stock only sets an upper limit for harvest, in Eisenack et al. (2006) an increase in capital stock improves productivity of variable inputs, and capital adjustment may offset the negative effect of a declining fish stock on harvesting costs. Their open access model shows that overcapitalisation is inevitable because capital stock keeps rising even after harvest has started to decline. Singh et al. (2006) show that with a small fleet it is optimal to invest at a rate lower than the capital depreciation rate. As investments are continued and the fleet becomes middle sized, the optimal policy converts to one of zero investment, which continues to one of disinvestment as the fleet increases and the marginal value of the capital stock falls below the resale value. They further argue that high capital adjustment costs require reduced harvest variability, even though this will reduce expected yields over time.

Besides irreversible investments the fishing industry is subject to high managements costs in terms of planning and meetings by policy makers. TAC levels in the European Union are currently determined in the Common Fisheries Policy (CFP) and are based on scientific advice and socio-economic interests (Rijnsdorp et al., 2007). Several times per year policy makers meet with scientists and representatives of the fishing industry to discuss results of newly available landings statistics, market sampling programs and research vessel surveys. TACs are determined in summer and in late autumn, where in the latter quotas are fixed for the following year. One of the reasons for the European Union to determine quota levels twice a year is for fishermen to be able to anticipate next year's quota, but this still does not allow making long term investment plans. In addition, the policy costs that are made in the process of quota re-adjustment are high and have been estimated at 78 million euro per year (EASE, 2007). These costs should not be ignored when setting the fisheries management regime and when adjusting policies such that they maximize overall benefits to society (Arnason, 2009). They have, however, not fully been accounted for in the literature, indicating that there may be a sub-optimal balance between economic and biological objectives.

In summary, it is unclear whether current fisheries policy strikes the right balance between the need to regularly adjust fisheries policy to new information on one hand, and the costs of gathering information and adjusting fisheries capital stock on the other hand. In the 2002 reform of the Common Fisheries Policy, a first step towards multiannual management plans was supposed to reduce this problem. Little is known, however, about the relative advantages and disadvantages of these plans (Salz 1996; EC 2002; Kell et al., 2006). Another management plan, which was adopted in the 2007 EC Council Regulation, aims at a reduction of fishing mortality that is supposed to be accomplished by changing TAC not more than 15% relative to the TAC of the previous year. This remains a management objective however, and has not been put into practice yet (ICES, 2009).

In order to get more insight into these two proposed management systems our objective is to compare harvest and investment decisions in the case of sole ownership without policy constraints, with annual constrained adjustment and multiannual adjustment of TAC, while accounting for management costs of quota adjustment. We present a dynamic model for a single-species fishery where a profit maximizing decision-maker determines harvest and investment levels for the European fishing industry. The problem is written in a stochastic dynamic programming framework and is solved with Value Function Iteration. The contribution of this paper to the literature is twofold. First, we address both the problem of irreversible capital adjustment and management costs that are incurred when managing the quota system. Second, we extend the discussion in the current literature by developing models for two proposed management systems that are yet to be put in practice, annual constrained quota adjustment and multiannual quota adjustment.

For the purpose of illustration we apply the model to North Sea plaice, which is one of the main commercially exploited flatfish in the North Sea and is subject to increasing fishing pressure (Kell and Bromley, 2004). The paper is organized as follows. In section 2 we present the theoretical model for each of the management systems: sole ownership, annual constrained quota adjustment and multiannual quota adjustment. In the illustrative example in section 3 we apply the model to management of North Sea plaice. Results are presented in section 4 and a sensitivity analysis follows in section 5. The final section draws conclusions and discusses policy implications.

THE MODEL

In this section we first present the biological and economic sub-models, with the corresponding assumptions. We then write the problem in a stochastic dynamic programming framework for three management systems: sole ownership, annual constrained quota adjustment and multiannual quota adjustment.

Biological and economic sub-models

Based on the work of Gordon (1991), in a deterministic setting the fish stock is assumed to grow according to a logistic growth function:

$$G_t = rx_t \left(1 - \frac{x_t}{M}\right) \quad (1)$$

where G_t denotes the growth rate, x_t is the fish population biomass, r is the intrinsic growth rate and M represents the carrying capacity of the stock. To complete the Gordon-Schaefer model (Gordon, 1991; Schaefer 1957) harvest is represented by the following function:

$$\begin{aligned} h_t &= qe_t x_t \\ h_t &\leq \min(x_t, k_t) \end{aligned} \quad (2)$$

Harvest rate, h_t , is determined by fleet effort, e_t , and fish stock. The catchability coefficient, q , is assumed to be a constant and can be interpreted as share of fish stock per unit of effort. We introduce a harvest constraint, which states that harvest cannot exceed fish stock and capital stock, k_t . In order to present a more realistic setting of the problem we introduce stochasticity in the specification of the fish stock dynamics. The stock in period $t+1$, x_{t+1} , depends on the previous stock and a multiplicative iid random variable, z_t , that follows a Markovian process with known distribution. The Markovian process implies that the probability distribution at time t does not depend on previous periods:

$$x_{t+1} = z_t (x_t + G_t - h_t) \quad (3)$$

For dynamics of capital stock, k_t , we follow literature on irreversible investment in fisheries capital (McKelvey, 1983; Singh et al., 2006):

$$\begin{aligned} k_{t+1} &= k_t(1 - \gamma) + i_t \\ k_t, i_t &\geq 0 \end{aligned} \quad (4)$$

This means that next period's capital stock, k_{t+1} , is determined by its current value, corrected for a deterministic vessel depreciation rate, $\gamma \in [0,1]$, and capital investment, i_t . Non-negativity constraints hold for capital stock and investment. The non-negativity of gross investment captures the irreversibility constraint that the fisherman faces. For harvest revenue, R_t , we follow Singh et al. (2006) and assume that harvest determines the market price of fish according to $p = a - bh_t$, which results in:

$$R_t = (a - bh_t)h_t \quad (5)$$

Harvesting costs, C_t , are defined as:

$$C_t = c_e e_t + c_R R_t \quad (6)$$

where cost of effort, c_e , and labour cost, c_R , are constant costs per unit of effort, e_t , and revenue, R_t , respectively. Effort costs include fuel and maintenance costs. Following McConnell and Price (2006) and Elliston and Cao (2006), we include crew costs as a constant share per unit of revenue. Finally, investment costs, $c_i i_t$, are determined by a constant cost per unit of investment.

Sole owner without policy constraints

In this section we present the model of a system without policy constraints, in which a sole decision maker decides on the level of harvesting and the level of investment. This setting serves as a basis on which following scenarios can be built. In this stochastic dynamic model a sole owner chooses levels of harvest and investment that maximize expected current discounted net benefits:

$$\max_{h_t, i_t} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t (NB_t) \right\}, \quad (7)$$

s.t.

$$h_t = qe_t x_t \quad (2)$$

$$x_{t+1} = z_t (x_t + G_t - h_t) \quad (3)$$

$$k_{t+1} = k_t (1 - \gamma) + i_t \quad (4)$$

where E_0 is the expectations operator, β is the discount factor and net benefits, NB_t , are $R_t(h_t(x_t)) - C_t(e_t, R_t(h_t(x_t))) - c_i(k_{t+1} - (1 - \gamma)k_t)$, which are harvest revenues minus harvest and investment costs. To understand decision making under uncertainty it is useful to analyze the problem in a stochastic dynamic programming framework. Following the literature on stochastic dynamic programming (Howard, 1960; Judd, 1998), we formulate the Bellman equation as follows:

$$V(x, k) = \max_{k', x'} \left\{ NB(x, k, h, k') + \beta E[V(x', k')] \right\} \quad (8)$$

where $NB(\cdot)$ is the current value of the fishery and $V(\cdot)$ is its discounted future value. The expectations operator, E , holds the transition probabilities of moving from a given current state of fish stock to next period's fish stock. It is sufficient to optimize current actions, conditional on future states being optimal. Choosing future states of capital stock, k' , and fish stock, x' , is therefore the same as choosing current levels of harvest and investment.

In order to solve the model numerically we use the value function iteration method. This is an iterative method which allows to establish the value function by means of iteration. The process converges until the value function has been established with a sufficient accuracy. In order to start the value iteration process, and because we do not know the exact form of the value function, we have to make an initial guess of the value function, V_0 . Iterations continue until the initial guess converges to the unique fixed point where $V_{t+1} - V_t$ is smaller than some convergence criterion. Because state transitions take place at discrete times, we need to discretise the number of states. Let us denote the grid of the state space of fish stock, x , in the row vector $\{x = x_0, x_1, x_2, \dots, x_{\dim x}\}$ and the grid of capital stock, k , in the row vector $\{k = k_0, k_1, k_2, \dots, k_{\dim k}\}$. The value function is represented by a 2-dimensional matrix of $\dim x \times \dim k$ over which iterations continue until the value function converges. By deriving first order conditions from the Bellman equation and applying the envelope theorem, we obtain a system of differential equations, Euler equations, which in turn enable us to get insight into the benefits of changing the control variables. The Euler equation of capital stock is:

$$c_i \gamma = \beta E \left\{ -C'_{e_k} \right\} \quad (9)$$

where the LHS is the cost of an additional unit of capital investment and the RHS is the discounted expected decrease in harvesting costs that result from adding a unit of capital stock. The Euler equation of fish stock is:

$$R_h - C_h = \beta E \left\{ R'_x - C'_x \right\} \quad (10)$$

where the LHS is the marginal net benefit of harvesting a unit of fish stock today and the RHS is the shadow value of the fish stock, which is the discounted expected marginal net benefit of leaving a unit of fish stock in the ocean, adding it to the future stock. The shadow value of the fish stock thus represents the marginal contribution to the maximized value from a unit increase in the fish stock.

Annual constrained quota adjustment

In this section we present the stochastic dynamic programming problem for the case where a sole decision maker, for instance the European Union, determines annual harvest and investment levels for the fishing industry. Following the management objective of reducing annual harvest fluctuation, we extend the sole owner's problem by assuming that annual adjustment of harvest is rigid. This is translated in a constraint on harvest change, by means of a rigidity measure, with respect to harvest in the previous period, h_{t-1} . We introduce harvest, h_t , as a new state variable and we introduce a rigidity parameter, $\alpha \in [0,1]$. A similar study has been done by Kell et al. (2005), where they call this constrained harvest system a harvest control rule and where α is referred to as a bound on annual fluctuation in TAC. Kell et al. analyze the path of fish stock growth towards the equilibrium but do not account for economic variables. In our study we assume that a rigidity of zero (i.e. $\alpha = 0$) means that the system is perfectly flexible and harvest can be changed without being constrained. A rigidity level of one (i.e. $\alpha = 1$) indicates perfect rigidity, so that $dh_t = 0$ and thus $h_t = h_{t-1}$. Instead of optimizing harvest we are now interested in the optimal change of harvest, dh_t , given any level of harvest in the previous period, h_{t-1} . The corresponding harvest dynamics are:

$$h_t = h_{t-1} + dh_t \quad (11)$$

The objective of the decision maker is to maximize expected current discounted net benefits and determine annual levels of investment and change in harvest:

$$\max_{dh_t, i_t} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t (NB_t) \right\}, \quad (12)$$

s.t. equations (2)-(4) , (11) and the following linear inequalities:

$$dh_t \geq -h_{t-1}(1 - \alpha) \quad (13)$$

$$dh_t \leq (\min(x_t, k_t) - h_{t-1})(1 - \alpha) \quad (14)$$

The linear inequality in equation (13) indicates that the change in harvest must be at least equal to or greater than the negative of the given harvest in the previous period, $-h_{t-1}$, which in turn is corrected for the rigidity level. In other words, with respect to h_{t-1} harvest can decrease until current harvest, h_t , is zero. This is because harvest can never become negative. As we constrain the system, however, current harvest must be greater than zero (depending on the level of rigidity) and the decrease in harvest, dh_t , is thus no longer greater than $-h_{t-1}$ but is now greater than $-h_{t-1}(1 - \alpha)$. Similarly, in equation (14) the change in harvest is at least equal to or smaller than the difference between the maximum possible current harvest, $\min(x_t, k_t)$, and the harvest in the previous period, h_{t-1} , which in turn is corrected for rigidity. Harvest can thus increase, dh_t , until the maximum possible change, $\min(x_t, k_t) - h_{t-1}$, is reached. In the constrained case, however, the change in harvest must be lower than this maximum possible change, again depending on the level of rigidity. The corresponding Bellman equation is:

$$V(x, k, h_{prev}) = \max_{k', x', h} \left\{ NB(x, k, h_{prev}, k') + \beta E[V(x', k', h)] \right\} \quad (15)$$

where h_{prev} is harvest of the previous period. Now choosing future states of capital stock, k' , fish stock, x' , and current harvest, h , is the same as choosing current levels of change in harvest, dh , and investment, i . A more rigid system will provide more certainty for fishermen as to what next year's quota will be. Investment can therefore be made with more certainty as well. In a more rigid system harvest will deviate less from previous harvest than in a more flexible system. Thereby, the smaller the change in harvest, the smaller the absolute value of annual investments.

Multiannual quota adjustment

Management costs, i.e. the costs of operating the quota management system, have not been studied extensively in the literature (Arnason et al., 2000). These costs include costs for research, implementing policy changes, monitoring and administrating them. According to Arnason et al. (2000) it has been widely assumed that the management costs are relatively small compared to their benefits and they are therefore not included in theoretical models. Exceptions are Anderson and Lee (1986) and Jon and Andersen (1985), who were the first to explicitly account for these management costs. They recognized that the literature thus far had not dealt with implementation and enforcement activities. Their results agree with Arnason et al. (2000) in that higher fishing effort and lower optimal biomass levels are generated when accounting for management costs. The assumption of low management costs has been contradicted in a recent study by Arnason (2009). It is argued that setting and enforcing bio-economic fisheries restrictions is costly and that these management costs represent a net economic loss. Other studies that stress policy costs date from the 1990s, showing for the United Kingdom a 7.5% management cost as percentage of the harvest value (Hatcher and Pascoe 1998), for the USA, Norway and Newfoundland 15%, 8% and 15-25% (Millazo 1998), and, for Iceland, Newfoundland and Norway, 3%, 15-25% and 10% (Arnason et al., 2000). Wallis and Flaaten (2003) find for 26 OECD countries that management costs are on average 6%. More recently, Simmonds (2007) finds that policy costs for North Sea herring amount to 2.5% of landed value.

Whether management costs are low or high, they should not be ignored when maximizing net benefits and determining optimal harvest. In the 2002 reform of the Common Fisheries Policy, a first step towards multiannual management plans was supposed to reduce the problem of the need to regularly adjust quotas to new information on one hand and the system's management costs. As there is little known about these proposed plans, we introduce a model for multiannual quota adjustment. We no longer adjust quota on an annual basis, but we fix harvest for a longer period of time, while accounting for the management costs. It is thereby assumed that the quota is always fully harvested. In the period that harvest is fixed capital stock may still be adjusted on an annual basis, to prepare for future fleet capacity. Theoretically, an unconstrained system generates higher values than an unconstrained system. There are two reasons, however, for modelling a constrained system. First, it is assumed that by keeping quotas fixed for more than one year management costs are reduced. Second, fishermen will have more certainty as to what next year's quota will be so that capital can be adjusted correspondingly, and overcapitalization can be prevented. We introduce this frequency of harvest adjustment as a new parameter, $\tau = 1, 2, 3, \dots$, where for $\tau = 1$, $h_{t=1} \neq h_{t=2} \neq h_{t=3} \neq h_{t=4} \neq \dots$; for $\tau = 2$, $h_{t=1} = h_{t=2}$, $h_{t=3} = h_{t=4}, \dots$; and for $\tau = 3$, $h_{t=1} = h_{t=2} = h_{t=3}$, $h_{t=4} = h_{t=5} = h_{t=6}, \dots$. In order to account for management costs, we follow Arnason (2009) and introduce the following management cost function, MC_t :

$$MC_t = c_M \left(h_t^{so} - h_t \right)^2 \frac{1}{\tau} \quad (16)$$

where c_M stands for the unit management cost, h_t^{so} is the optimal harvest level under no management, which is the sole owner's optimal harvest rate, and h_t is the optimal harvest level in the case of multiannual quota adjustment. As in Arnason (2009) the convex nature of the management cost function reflects how costs become higher as the deviation between the managed harvest and the unmanaged harvest increases. The term $\frac{1}{\tau}$ indicates that the annual management costs decrease as the number of years for which the harvest is fixed increases. The objective of the decision maker is to maximize expected current discounted net benefits minus management costs and determine multiannual harvest levels and annual levels of investment:

$$\max_{h_t, i_t} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t (NB_t - MC_t) \right\}, \quad (17)$$

s.t. equations (2), (3) and (4). The corresponding Bellman equation remains as in equation (8). From a theoretical point of view it is expected that under unchanged annual costs the unconstrained quota system always generate higher values than a constrained system. Due to the convex nature of the management cost function, however, and the decreasing annual costs, this may lead to different results.

APPLICATION TO NORTH SEA PLAICE

As an illustration, we apply the model to North Sea plaice, which is the main commercially exploited flatfish in the North Sea and is subject to increasing fishing pressure (Kell and Bromley, 2004). Landings of North Sea plaice are shared between EU countries, with Dutch vessels landing 40%, the UK 23%, Danish landings are 20% and Belgium, Germany, France and other countries land 17% (Cefas 2008). In 2007 ICES classified that the spawning stock biomass was at risk of reduced reproductive capacity and that the stock was in a state of overexploitation (Cefas 2008), which means that fishing mortality was higher than the highest yield. In 2008 and 2009, however, ICES reported a full reproductive stock capacity (ICES, 2008; ICES, 2009). The status of fishing mortality in relation to highest yield has gone from overexploited in 2007 to overfished in 2008 and 2009.

Biological sub-model

Growth of North Sea plaice has changed over the years and the fishing industry has played a role in this. Beam trawling may have caused a shift from low-productive, long-lived species to high-productive, short-lived species (Rijnsdorp and Millner, 1996). Growth rates have been determined for different locations, ages, sizes etc., with ICES contributing for a great deal to the literature (Rijnsdorp and Millner, 1996; Grift et al., 2003; Kell and Bromley, 2004; Pilling et al., 2008). Because ICES plays an important research and advisory role in fisheries management in the European Union we follow ICES data on North Sea plaice in this study. For the biological sub-model we assume that plaice grows according to a logistic growth function, where the intrinsic growth rate is 0.74 (FishBase). Based on Schaefer (1957) and Haddon (2001) we assume that the carrying capacity of a fish stock is twice the maximum sustainable yield. ICES proposed to maintain the spawning stock biomass above 230 mln kg (ICES, 2007; ICES, 2008). We therefore adopt a carrying capacity of 460 mln kg. Following studies on Northeast Atlantic flatfish (Kell et al., 2005), on the Dutch beam trawler fleet (Gillis et al., 2008) and on North Sea Plaice (Pilling et al., 2008), the iid random variable is assumed to have a lognormal distribution with mean 2.98 and standard deviation 0.68.

Economic sub-model

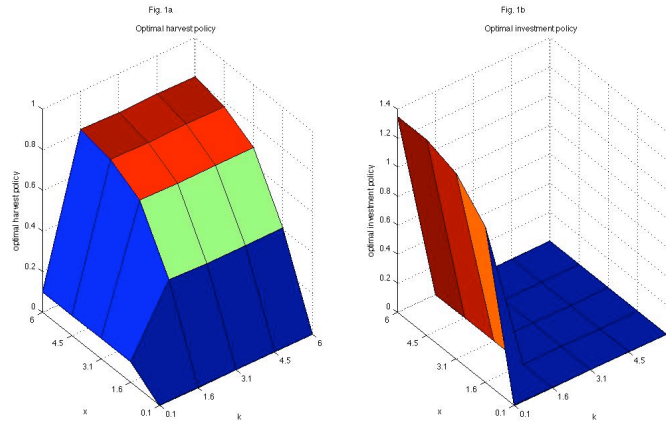
For the economic sub-model data are obtained from Van Balsfoort (2006), Taal et al. (2008), and EC (2007). Since the Netherlands have the largest share in North Sea plaice fishing, we use data on the Netherlands as representative for the remaining EU countries that exploit plaice in the North Sea. Capital is measured in terms of the engine capacity of the vessels and the number of days at sea, expressed in mln horse power days (hpd). It is assumed that each vessel operates on 978 hp (EC, 2007). Catchability, which is interpreted as catch per hpd per kg of fish stock, is 0.044 (Fraser et al., 2007). The parameters of the inverse demand function are derived from 1997-2007 data on market price of North Sea plaice and on landings; a is 2.9 and b is 0.01. Effort costs were 410,000 euro per vessel (Taal et al. 2008), which is equivalent to 1.72 euro per unit of effort. Cost per unit of investment is 12.33 euro per hpd, which is derived from the total investment costs over 2007, the invested hp and the number of sea days. In 2007 crew costs in the Netherlands were 0.19 euro per unit of revenue. In order to complete the dynamics of capital stock, we assume that the relevant vessel depreciation rate is 10%, which allows for a major overhaul of the vessel at least every ten years. Finally, a management cost of 5.5 euro per unit of revenue is derived from Hatcher and Pascoe (1998), Millazo (1998), Arnason et al. (2000), Wallis and Flaaten (2003) and Simmonds (2007).

RESULTS

The optimal policy of the sole owner without policy constraints

The sole owner's optimal harvest and investment policies are plotted in figure 1(a-b), where fish stock and harvest are measured in 100 mln kg and investment is measured in mln hpd. Figure 1a shows that the optimal harvest policy increases both in fish stock, x , and in capital stock, k . The results are in line with results in Singh et al. (2006). The graph shows that the sole owner smoothes catch over time as opposed to harvesting the entire stock at once. As it is discussed in Singh et al. (2006), the sole owner has the option to harvest as much of the current fish stock as the available capital stock allows. The reason why this does not happen is that as more fish is caught with the available capital stock, the smaller is the harvest per unit of capital stock. Decreasing harvest per unit of capital stock means increasing operating costs, which in turn leads to diminishing marginal net benefits. More capital must therefore be added to the fleet, but as capital adjustment costs add to the diminishing marginal net benefits, small adjustments are made as opposed to large adjustments that can potentially harvest the entire current fish stock. It is thus reflected in how a trade-off is made between harvesting now and leaving some fish for future periods. The same can be said for the optimal investment policy in figure 1b, where it is shown that as current capital stock increases, less capital is

added to the fleet. The two graphs show that both decisions can only be made based on known current capital stock and known current fish stock.



The optimal policy of the annual constrained quota adjustment

In this scenario we introduced a rigidity parameter α , where an α of zero indicates complete flexibility of harvest change and an α of one is complete rigidity. The EU management objective has been to set this rigidity to 15%, but we ran the model for $\alpha = \{0, 0.1, \dots, 0.5\}$. The optimal harvest policy is plotted in figure 2(a-f). Each graph shows, as in the sole owner’s problem, that the optimal harvest policy increases in x and decreases in k . Each graph has 3 plots, which represent the optimal harvest policy at low, median and high levels of previous harvest, h_{prev} . Previous harvest was introduced as a new state variable, which means that besides x and k also the level of previous harvest affects the optimal harvest policy. The influence, however, changes as the system becomes more rigid. Each figure shows that as previous harvest increases the optimal harvest policy decreases. But as the system becomes more rigid, reflected in the increasing α , the previous harvest has less of an effect the optimal harvest policy. In fact, at low and middle levels of previous harvest the policy is little affected, but at high levels of previous harvest two things can be observed: the optimal harvest increases and becomes flatter in the sense that harvest changes less as different combinations of x and k . These results in fact reflect the restriction that has been placed on the system in order to make it more rigid.

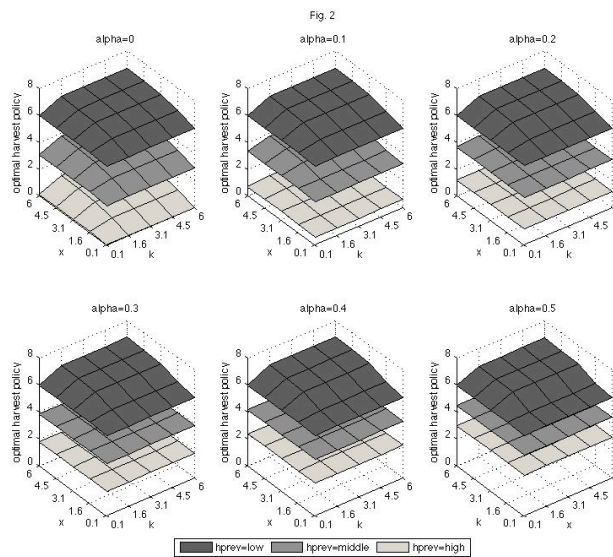
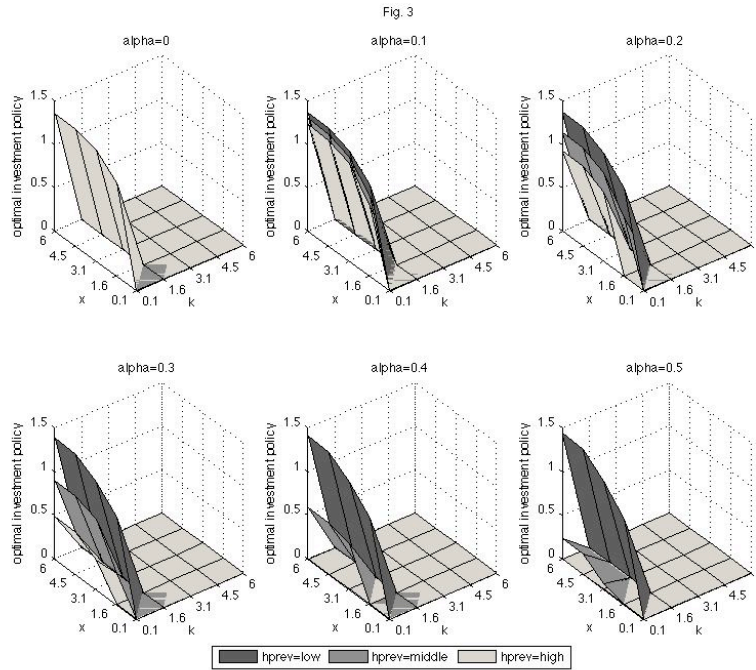


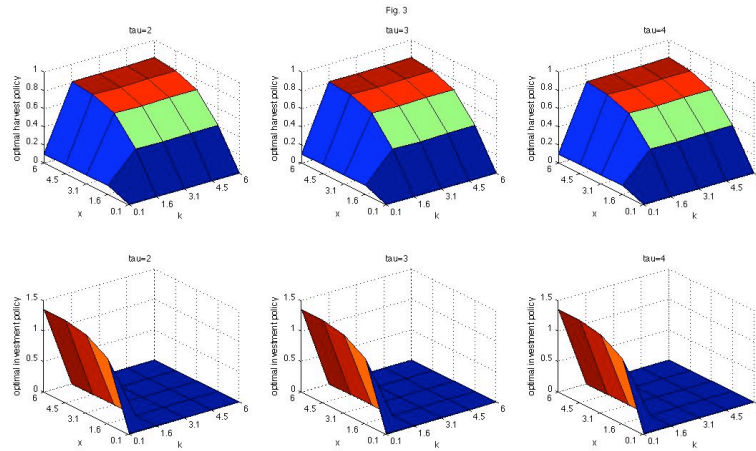
Figure 3 plots the optimal investment policy at different levels of rigidity and different levels of previous harvest. Consider figure 3a first. The complete flexibility in this case shows that the optimal harvest policy is not affected by previous harvest, simply because there is no constraint on harvest at and α of zero. In fact, the result is the same as

in the sole owner's problem. Consider figures 2(b-f) now. It is expected that the optimal investment policy follows the optimal harvest policy. At low and middle levels of previous harvest there was little change in the optimal harvest as the system became more rigid. With unchanging harvest also the investment path remains the same at an increasing rigidity. As the rigidity increases, however, the optimal investment policy decreases at high levels of previous harvest. This result reflects the optimal harvest policy, which showed that harvest both increased and became flatter.

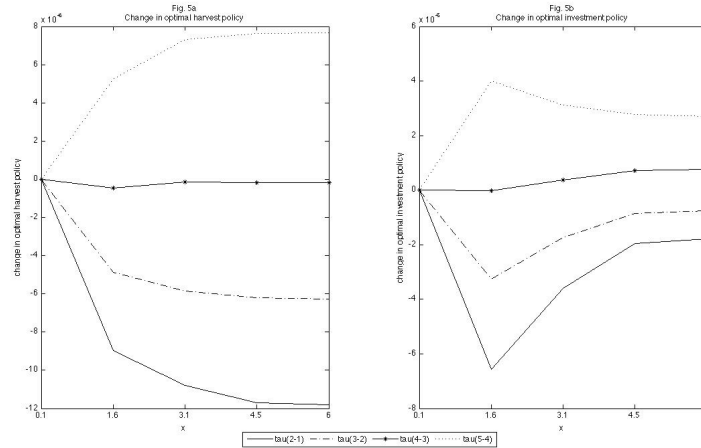


Optimal policy of the multiannual quota system

In this scenario we introduced different frequencies of harvest change, represented by the parameter τ . The model was run for $\tau = \{1, 2, \dots, 5\}$. Figure 3(a-f) presents the result of frequencies of 2, 3 and 4 years. Graphs (a-c) show the optimal harvest policy and graphs (d-f) show the optimal investment policy. Results of multiannual quota adjustment are similar for different frequencies of harvest change; no change in optimal harvest is observed. And as harvest does not show a change as τ increases, also investment does not change.



To shed some light on the solutions under the different frequencies of harvest change, figure 4(a-b) shows the changes in the optimal policies as the frequency is adjusted. Though the changes are subtle, it can be observed that as τ is increased the changes in the optimal policies decrease and in fact become positive once τ goes from 4 to 5. The change is zero when a switch is made between τ of 3 and 4. It can also be observed that the changes increase as the fish stock becomes larger, but eventually stabilize.



SENSITIVITY ANALYSIS

CONCLUSION

This paper provides a bioeconomic model that optimizes both harvest and investment decisions for a fishery that is subject to stochastic fish stock dynamics. The problem is presented in a stochastic dynamic programming framework and is numerically solved with Value Function Iteration. The contribution of this paper to the literature is twofold. First, we jointly address both the problem of irreversible capital adjustment and management costs that are incurred when managing the quota system. Second, we extend the discussion in the current literature by developing models for two proposed management systems that are yet to be put in practice, annual constrained quota adjustment and multiannual quota adjustment.

Three scenarios are developed and applied, for illustration, to North Sea plaice: the sole owner's problem without policy constraints, annual constrained quota adjustment and multiannual quota adjustment. In the first scenario a sole owner's problem without policy constraints is solved in order to get insight into the basic problem. Uncertainty in fish stock dynamics is included as a multiplicative iid random variable. In this scenario it shows that optimal harvest and investment policies both increase in fish stock and in capital stock. The sole owner rather smooths catch over time than harvesting the entire available fish stock, because of decreasing harvest per unit of capital stock, diminishing marginal net benefits and capital adjustment costs. In the second scenario we extend the model to account for annual constrained quota adjustment. This model is developed as a result of the management plan of the EU to reduce annual harvest fluctuation by 15%. In the model this is translated into harvest being constrained by harvest in the previous period, by means of a rigidity parameter. It shows that the optimal harvest policy not only increases in fish stock and in capital stock, but also decreases in previous harvest. In addition, as the system becomes more rigid, optimal harvest increases at high levels of previous harvest and becomes flatter. The optimal investment policy is adjusted correspondingly, and thus decreases at increasing levels of previous harvest. In the third scenario another extension is made to the problem of the sole owner without policy constraints, in order to model the EU's multiannual management plans. The restriction on harvest, which is represented by a parameter for the frequency of harvest change, reflects the multiannual adjustment of fish quota. It shows that as we lower the frequency of harvest change, also changes in the optimal harvest and investment policies decrease and become zero when we go from a frequency of 3 years to a frequency of 4 years.

A sensitivity analysis is yet to be performed, which will allow us to analyze the effect of changes in the parameter values on the optimal policies.

References

- Arnason, R., 2009. Fisheries management and operations research. *European Journal of Operational Research* 193(3): 741-751.
- Arnason, R., Hannesson, R., Schrank, W. E., 2000. Costs of fisheries management: the cases of Iceland, Norway and Newfoundland. *Marine Policy* 24(3): 233-243.
- Boyce, J. R., 1995. Optimal Capital Accumulation in a Fishery: A Nonlinear Irreversible Investment Model. *Journal of Environmental Economics and Management* 28(3): 324-339.
- Bulte, E., Pennings, J., 1997. A Note on Overfishing, Fishing Rights and Futures Markets. *European Journal of Law and Economics* 4(4): 327-335.
- Cefas, PLAICE in the North Sea (ICES Sub-area IV) – 2008.
- Charles, A. T., 1983. Optimal fisheries investment under uncertainty. *Canadian Journal of Fisheries & Aquatic Sciences* 40(12): 2080-2091.
- Clark, C. W., Clarke, F. H., Gordon, R. M., 1979. The Optimal Exploitation of Renewable Resource Stocks: Problems of Irreversible Investment. *Econometrica* 47(1): 25-47.
- EASE, 2007. Quality of life and management of living resources programme (1998-2002) - Final Report. Reporting period 2002-2006.
- Eisenack, K., Welsch, H., Kropp, J. P., 2006. A qualitative dynamical modelling approach to capital accumulation in unregulated fisheries. *Journal of Economic Dynamics and Control* 30(12): 2613-2636.
- Elliston, L., Cao, L., 2006. An agent-based bioeconomic model of a fishery with input controls. *Mathematical and Computer Modelling* 44(5-6): 565-575.
- European Commission, 2002. Communication from the Commission to the Council and the European Parliament laying down a Community Action Plan for the conservation and sustainable exploitation of fisheries resources in the Mediterranean Sea under the Common Fisheries Policy. COM(2002) 535 final, Brussels.
- European Commission, 2007. Economic performance of selected EU fishing fleets. Summary document prepared by the economic unit of DG Fish.
- Grift, R. E., Rijnsdorp, A. D., Barot, S., Heino, M., Dieckmann, U., 2003. Fisheries-induced trends in reaction norms for maturation in North Sea plaice. *Marine Ecology Progress Series* 257: 247-257.
- Haddon, M., 2001. *Modelling and quantitative methods in fisheries*. Florida: Chapman & Hall/CRC.
- Hatcher, A., Pascoe, S., 1998. Charging the UK Fishing Industry. A report to the Ministry of Agriculture and Food. Centre for the Economics and Management of Aquatic Resources (CEMARE), University of Portsmouth.
- Howard, R.A., 1960. *Dynamic programming and Markov Process*. MIT Press & John Wiley, Cambridge, USA.
- ICES, 2007. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK), ICES Headquarters. ACFM: 35. <http://www.ices.dk/reports/ACFM/2006/WGNSSK/directory.asp>.
- ICES, Advice 2008. Book 6, section 6.4.7 Plaice in Subarea IV. <http://www.ices.dk/committe/acom/comwork/report/2008/2008/ple-nsea.pdf>
- Judd, K., 1998. *Numerical Methods in Economics*, MIT Press, Cambridge, MA.
- Kell, L. T., Bromley, P. J., 2004. Implications for current management advice for North Sea plaice (*Pleuronectes platessa* L.): Part II. Increased biological realism in recruitment, growth, density-dependent sexual maturation and the impact of sexual dimorphism and fishery discards. *Journal of Sea Research* 51(3-4): 301-312.
- Kell, L. T., Pilling, G. M., Kirkwood, G. P., Pastoors, M. A., Mesnil, B., Korsbrekke, K., Abaunza, P., Aps, R., Biseau, A., Kunzlik, P., Needle, C. L., Roel, B. A., Ulrich, C., 2006. An evaluation of multi-annual management strategies for ICES roundfish stocks. *ICES J. Mar. Sci.* 63(1): 12-24.
- McConnell, K. E., Price, M., 2006. The lay system in commercial fisheries: Origin and implications. *Journal of Environmental Economics and Management* 51(3): 295-307.
- McKelvey, R., 1983. The fishery in a fluctuating environment: Coexistence of specialist and generalist fishing vessels in a multipurpose fleet. *Journal of Environmental Economics and Management* 10(4): 287-309.
- McKelvey, R., 1985. Decentralized regulation of a common property renewable resource industry with irreversible investment. *Journal of Environmental Economics and Management* 12(4): 287-307.
- Millazo, M., 1998. Subsidies in world fisheries: a re-examination. World Bank Technical Paper No. 406, Fisheries Series, Washington.
- Pilling, G. M., Kell, L. T., Hutton, T., Bromley, P. J., Tidd, A. N., Bolle, L. J., 2008. Can economic and biological management objectives be achieved by the use of MSY-based reference points? A North Sea plaice (*Pleuronectes platessa*) and sole (*Solea solea*) case study. *ICES J. Mar. Sci.* 65(6): 1069-1080.

- Rijnsdorp, A. D., Daan, N., Dekker, W., Poos, J. J., Van Densen, W. L. T., 2007. Sustainable use of flatfish resources: Addressing the credibility crisis in mixed fisheries management. *Journal of Sea Research* 57(2-3): 114-125.
- Rijnsdorp, A. D., Millner, R. S., 1996. Trends in population dynamics and exploitation of North Sea plaice (*Pleuronectes platessa* L.) since the late 1800s. *ICES J. Mar. Sci.* 53(6): 1170-1184.
- Roughgarden, J., Smith, F., 1996. Why fisheries collapse and what to do about it. *Proceedings of the National Academy of Sciences* 93: 5078-5083.
- Salz, P., (ed.), 1996. Bio-economic evaluation of multi-species and multiannual fisheries management measures. Onderzoekverslag 150, LEI-DLO, The Hague.
- Schaefer, M.B., 1957. Some considerations of population dynamics and economics in relation to the management of the commercial marine fisheries. *J. Fisheries Res. Board Canada* 14(5): 669-81.
- Scott Gordon, H., 1991. The economic theory of a common-property resource: The fishery. *Bulletin of Mathematical Biology* 53(1-2): 231-252.
- Seafish, 2008. Fisheries Management Issues Report. http://www.seafish.org/upload/file/economics/FMIR_October_2008.pdf
- Sethi, G., Costello, C., Fisher, A., Hanemann, N., Karp, L., 2005. Fishery management under multiple uncertainty. *Journal of Environmental Economics and Management* 50: 300-318.
- Singh, R., Weninger, Q., Doyle, M., 2006. Fisheries management with stock growth uncertainty and costly capital adjustment. *Journal of Environmental Economics and Management* 52(2): 582-599.
- Taal, C., Bartelings, C., Beukers, R., van Duijn, A., Klok, A., Van Oostenbrugge, J.A.E., Smit, J.P.G., 2008. Visserij in cijfers 2008. LEI, Den Haag.
- Van Balsfoort, G., 2006. Vissen met tegenwind: advies TaskForce Duurzame Noordzee visserij. Dutch Fish Product Board, Rijswijk.
- Wallis, P., Flaaten, O., 2003. Fisheries management cost: concepts and studies. In *The cost of fisheries management*, ed. Schrank, W.E., Arnason, R., Hannesson, R., 2003: 211-223. England: Ashgate Publishing