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Multiannual adjustment of fish quota: growth uncertainty and management costs

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Multiannual adjustment of fish quota: growth uncertainty and management costs *

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North Sea fisheries are managed by the European Union (EU) through a system of annual quota. Due to uncertainty about future fish stocks, yearly revisions of these policies lead to fluctuation in quota, which in turn affects harvest and investment decisions of fishermen. Determination of quota also requires high management costs in terms of obtaining information and negotiations between experts and policy makers. To reduce both quota fluctuation and annual management costs, the EU has proposed a system of multiannual quota. This may lead to more fish stock fluctuation as multiannual quota does not allow the EU to intervene in time. In addition, reduced management costs only have a positive effect on social benefits if these costs are offset by gains through less volatile capital adjustment. The novelty of this paper is that we simultaneously address the problem of fluctuating quota and high management costs. Does multiannual quota lead to less fluctuation in quota? And, do reduced management costs improve social benefits? We develop a bi-level Stochastic Dynamic Programming model, where at level one, the EU determines the quota that maximizes social benefits. At level two, myopic fishermen decide on their harvest and investment levels, subject to the quota.

Key words: fisheries management, multiannual quota, management costs, stochastic dynamic programming

1. Introduction

Total Allowable Catch (TAC) of North Sea fish species are established on an annual basis as new catch and biological survey data become available. Annual adjustment of quota results in overcapacity for fishermen [10] and high management costs for the EU [2].

Natural fluctuation in stock growth provides a challenge to management of fish species, often resulting in sub-optimal adjustment and annually fluctuating quota [6]. Fishermen in return are confronted with unstable quota. As capital adjustment is costly, adjusting capital stock each year to the new required level is cumbersome. Due to irreversibility of investment in capital stock and with fishermen revealing short term behaviour, the result is often volatile capital adjustment [3] or even overcapacity [10].

Management costs, i.e. the costs of operating the quota management system, have been estimated at 78 million euro per year for 13 European countries [8]. Studies that derive management costs on a country or species basis show that these costs range from 2.5% of harvest value, for North

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Sea herring, to 25% of harvest value for Iceland, Newfoundland and Norway [14, 25, 1, 35, 30]. Discussions about whether these management costs are relatively small to benefits [1] or whether they represent a net economic loss [2] are ongoing. This implies that management costs should not be ignored when adjusting quota such that they maximize social benefits [2]. To the best of our knowledge, they have not been fully accounted for in the literature on optimal policies, meaning that there may be a sub-optimal balance between economic and biological objectives.

In the 2002 reform of the Common Fisheries Policy, a first step towards multiannual management plans was proposed to reduce the problem of fluctuating quota and high annual management costs. On one hand, by keeping quota constant for multiple years, fishermen can reduce capital volatility. In addition, fewer meetings between policy makers and scientists are required, which reduces annual management costs and potentially increases social benefits. On the other hand, policy makers are reduced in their ability to adjust quota to new developments in the fish stock.

Studies that evaluate multiannual management plans include [19], [20], [29] and [22]. [20] examines whether the fish stock remains above the assigned precautionary limit of biomass. It shows that multiannual management is more likely to speed-up recovery in the stock than annual management, which in turn may lead to less restricted harvest levels. A reason for this finding, however, is not provided. A counter-argument is raised in [29], where it is said that multiannual management is less effective because of the higher risk of falling below the precautionary level. Another counter-argument in [29] states that due to uncertainty in future fish stock, it is impossible to achieve interannual stability of quota. Unless quota are kept at very conservative levels, fixation may be done at the cost of reducing sustainability of fish species [22]. In turn, the consequence may be even greater fluctuation of quota and greater volatility in capital adjustment [19]. While above studies are based on landing data [20] or stock and landing data [29, 22], it remains unknown to what extent restrictions, in terms of quota, change under multiannual management plans and whether results of above studies hold when uncertainty and dynamics in biological and economic factors are accounted for. Also the reduction in annual management costs needs to be accounted for. If capital adjustment costs increase because of greater volatility in quota, this may be offset by reduced annual management costs and may even have a positive effect on social benefits. There is still much to learn about the relative advantages and disadvantages of multiannual management plans [22].

We therefore formulate two research questions: (i) does multiannual quota reduce fluctuation in quota? And (ii) does a reduction in annual management costs offset the reduced flexibility in quota adjustment? With respect to fishermen that behave myopically, the subquestion that follows is, does capital adjustment become less volatile and is overcapacity reduced under multiannual quota?

We address these questions with a bi-level dynamic model that includes both dynamics of fish stock and capital stock. On the first level, the EU determines the quota that maximizes social benefits. On the second level, myopic fishermen operate under a system of restricted open access, which means that their harvest and investment decisions are subject to the quota that the EU determines at level one. The problem is written in a Stochastic Dynamic Programming (SDP) framework and is solved with Value Function Iteration.

The contribution of this paper to the literature is that the problems of fluctuating quota and high management costs in the current system of annual quota are addressed simultaneously. For illustration we apply the model to North Sea plaice, which is one of the main commercially exploited flatfish in the North Sea. The paper is organized as follows. Section 2 presents the theoretical model. In an illustrative example in Section 3, the model is applied to management of North Sea plaice. Results are presented in Section 4, followed by a sensitivity analysis in Section 5. We conclude in Section 6 with a discussion.

2. The model

We present a bi-level Stochastic Dynamic Programming (SDP) model that includes dynamics of both fish stock and capital stock. On the first level, the EU determines the quota that maximizes social benefits. Quota may be fixed for multiple years, which are called multiannual quota. On the second level, myopic fishermen are subject to this quota and decide on their annual harvest and investment levels correspondingly.

2.1. The EU: a discrete-time stochastic dynamic programming model

The system starts at level one with the decision of the European Union, EU. The objective of the EU is to find the quota that maximizes the expected discounted social benefits given observed levels of fish stock and capital stock of fishermen. Social benefits, π_t, in any period t are:

$$\pi_t(x_t, k_t, Q_t) = R_t - c_{_E} E_t(x_t, k_t, Q_t) - c_{_R} R_t - c_{_i} i_t(x_t, k_t, Q_t) - c_{mc}/f, \tag{1}$$

where fish stock, x_t, and capital stock, k_t, are state variables and quota, Q_t, is the decision variable of the EU. Revenue $R_t = ph_t$ is fixed price p times harvest h_t, which in turn depends on effort, E_t. This effort level is decided by fishermen at level two of the model, where besides states x_t, k_t, quota Q_t is an input. Furthermore, $c_{_E}$ is the cost per unit of effort, $c_{_R}$ is the cost per unit of revenue, which represents crew costs, and $c_{_i}$ is the cost per unit of investment, i_t. Investment, i_t, is also decided on the second level and is a function of x_t, k_t and Q_t. Finally, the annual costs that the EU faces for adjustment of quota is assumed to be a constant amount c_{mc} spread over the number of years for which the quota is fixed, f. From here on we refer to f as the fixed quota period. Compared to yearly adjustment of quota, annual management costs reduce to a half when the fixed quota period consists of 2 year, they reduce to a third when the the fixed quota period consists of 3 years, and so on. The objective of the EU is then to determine the quota, Q_t, that maximizes expected discounted social benefits:

$$\max_{Q_t} \mathbb{E} \left\{ \sum_{t=0}^{T} \frac{\pi_t(x_t, k_t, Q_t)}{(1+\rho)^t} \right\}, \tag{2}$$

where decision Q_t is subject to

$$\begin{cases} 0 \leq Q_t \leq Q_{max} & \text{if } t \text{ is a multiple of } f \\ Q_t = Q_{t-1} & \text{otherwise} \end{cases} \tag{3}$$

In Equation (2), $\mathbb{E}$ stands for the expectation we take over current values of state variables fish stock, x_t, and capital stock, k_t, ρ is the discount rate and T is the planning horizon expressed in numbers of years. In order to maintain a sustainable fish stock and profitable fishery, the decision of Q_t is also based on dynamics in fish stock, x_t, and fishermen behaviour in terms of harvest and investment decisions, embedded in dynamics of capital stock, k_t:

$$x_{t+1} = x_t + z_t G_t - h_t \tag{4}$$

$$k_{t+1} = (1-\gamma) k_t + i_t. \tag{5}$$

Fish stock x_{t+1} in period $t+1$, depends on the previous stock, x_t, stochastic growth, $z_t G_t$, and harvest, h_t. We assume densitiy depended growth, $G_t = r x_t (1 - x_t/M)$, where r is the intrinsic growth rate and M is the carrying capacity. The growth shock, z_t is a multiplicative iid random variable that follows a Markovian process with known distribution. Capital stock, k_{t+1}, is determined by its previous value, k_t, diminished by a deterministic vessel depreciation rate, γ, and by capital investment, i_t. The quota decision of the EU is based on knowledge of harvest and investment levels of fishermen. Furthermore, the EU optimizes the quota at the beginning of each fixed quota period. If a fixed quota period consists of one year, $f = 1$, the quota is optimized in each year t and we have annual quota adjustment. If a fixed quota period consists of two years, $f = 2$, the quota is optimized in $t = 1$ and it is fixed in $t = 2$ at the level of $t = 1$. A fixed quota period of more than one year thus respresents multiannual quota.

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 [15, 18], we formulate the Bellman equation that represents a recursive relation:

$$V_t(x_t, k_t, Q_{t-1}) = \max_{Q_t} \begin{cases} \pi_t(x_t, k_t, Q_t) + \delta \mathbb{E}\left[V_{t+1}\left(x_{t+1}, k_{t+1}, Q_t\right)\right] & \text{if } t \text{ is a multiple } f \\ \\ \pi_t(x_t, k_t, Q_{t-1}) + \delta \mathbb{E}\left[V_{t+1}\left(x_{t+1}, k_{t+1} Q_{t-1}\right)\right] & \text{if } t \text{ is not a multiple } f \end{cases} \tag{6}$$

V_t is the value function, which represents the maximized value of the objective function from time t onwards, δ is the discount factor and $\mathbb{E}$ is the expectations operator that holds the transition probabilities of moving from a given current state of fish stock, x_t, to next period's fish stock, x_{t+1}. Multiannual adjustment is accounted for by assuming that Q_t is always optimized at the beginning of a new fixed quota period. In all other years, the quota of the previous period, Q_{t-1}, becomes a state variable and we fix Q_t to that level, $Q_t = Q_{t-1}$. We consider the model with discrete time steps and we solve the problem numerically using Value Function Iteration. This works as follows. At iteration t, we have an estimate of value function V_t. The Bellman equation is then applied to compute and update the estimated V_{t+1}. For a detailed explanation on the implementation of the value iteration process see [27].

2.2. Fishermen: myopic harvest and dynamic investment behaviour under restricted open access

We now present the decisions at level two, i.e. fishermen behaviour with respect to harvest and investment. It is first assumed that fishermen are homogenous and that they operate under restricted open access. This means that each individual fisherman operates as if it were open access, but all fishermen together are subject to a quota. Fishermen will only leave the fishery when rents have dissipated. In our model, a Spence harvest function describes the interaction between harvest and effort: $h_t = x_t(1 - e^{-qE_t})$, where q is a catchability coefficient [32]. Costs are a linear function in effort,

$$E_t = \frac{1}{q} ln(\frac{x_t}{x_t - h_t}), \tag{7}$$

expressed as the inverted Spence harvest function. Equating revenues, $R_t = ph_t$, and costs, $C_t = c_E E_t + c_R R_t$, and then solving for $\hat{x} = x_t$ gives the open access fish stock, which is the level of fish stock below which it is not profitable to harvest [4]:

$$\hat{x} = \frac{c_E}{pq(1 - c_R)}. \tag{8}$$

In [5], c^e/pq has been identified as the bioeconomic equilibrium escapement in the Spence model. At fish stock levels below $\hat{x}$ harvest is zero, so that in such a case a positive quota is not binding. We therefore assume that $Q_t = h_t = 0$ if $x_t < \hat{x}$.

Under pure open access, harvest takes place for a fish stock $x_t > \hat{x}$. In that case, the level of harvest is given by $h_t = (x - \hat{x})^+$, where the operator $(y)^+ = \max\{0, y\}$. In restricted open access, however, fishermen are also confronted with quota Q_t, such that

$$\hat{h}_t = \min\{(x_t - \hat{x})^+, Q_t\}. \tag{9}$$

Harvest is also determined by the available capital stock, k_t. This means that fishermen cannot harvest more than what their capital stock allows. Given the Spence harvest function and substituting capital stock k_t for effort E_t, provides the following myopic harvest rule:

$$h_t = min\{\hat{h}_t, x_t(1 - e^{-qk_t})\}. \tag{10}$$

Next we develop an investment rule based on similar assumptions as above, i.e. decisions are based on currently available and currently desired capital stock. The dynamic aspect of the investment rule is the assumption that the investment made in period t becomes available in the next period, $t+1$. Given the currently available capital stock, fishermen want to be able to fully harvest $\hat{h}_t$, which means that fishermen need to make sure that they have the corresponding capital stock. This capital stock is in fact the effort level required to harvest $\hat{h}_t$, so that $\hat{E}_t = \frac{1}{q} ln(x_t/(x_t - \hat{h}_t)$, where we invert the Spence harvest function and assume that effort and harvest are both functions of quota. Given the available depreciated capital stock, $(1-\gamma)k_t$, fishermen thus determine whether this is sufficient to harvest $\hat{h}_t$. If their available capital stock is smaller than the required effort, $\hat{E}_t$, they invest the difference so that the investment rule looks as follows:

$$i_t = max\{0, \hat{E}_t - (1-\gamma)k_t\}. \tag{11}$$

3. Application of the model to North Sea plaice

As an illustration, we apply the model to North Sea plaice, which is one of the main commercially exploited flatfish in the North Sea. Growth of North Sea plaice has changed over the years and the fishing industry has played a role in this. We follow ICES data on North Sea plaice in this study [28, 13, 21, 26] and we measure fish stock, harvest and quota in kton. To the best of our knowledge, the intrinsic growth rate of plaice, r, is not measured as such, which is why we assume the value of critical fishing mortality, F_{lim}, as growth rate, i.e. $r = 0.74$. Carrying capacity, M, is 460 kton, which is twice the maximum sustainable yield, i.e. the precautionary spawning stock B_{pa} [17]. The multiplicative iid random variable on fish stock growth, z_t, is based on a timeseries of North Sea plaice over the period 1957-2009 [16]. For this timeseries we assume a lognormal distribution [11, 26] with $\mu = -0.0126$ and $\sigma = 0.159$, so that $\mu + 1/2\sigma^2 = 0$ and the average multiplicative shock on growth is 1.

Economic data, for level one and two, are obtained from [34], [33], and [7]. Because 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. Effort and capital are measured in terms of engine capacity of vessels and number of days at sea, expressed in millions of horse power days, mln hpd.

At level one, the EU accounts for investment costs, where we assume per unit investment cost, c_i, of €$2.1 * 10^6$ per million horse power days, mln hpd. An annual management cost, c_{mc}, of €$5.29 * 10^6$ is derived from [14], [25], [1], [35] and [30]. We finally apply a discount factor, δ, of 0.95. At level two, we use a fixed fish price, p, of €$1.83 * 10^6$ per mln hpd, a per unit effort cost, c_E, of €$3.54 * 10^6$ per mln hpd, a per unit revenue cost, c_R, of 0.25%, and a vessel depreciation rate of $\gamma = 10\%$. Now we can derive open access fish stock, $\hat{x} = 185.6$ kton.

For the bounds of the state space of fish stock, we have $x \in [\hat{x}, M]$, taking $\hat{x} = 185.6$. Because of the assumption that $Q_t = h_t = 0$ if $x_t < \hat{x}$, we do not consider values below $\hat{x}$. From this assumption follows that a reasonable range for optimal quota is $Q \in [0, M - \hat{x}]$. Finally, for the bounds of the state space of capital stock we have $k \in [0, 74]$.

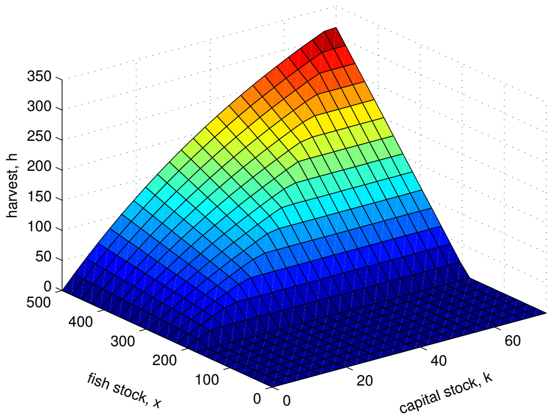

Figure 1 harvest, h_t, without quota restriction

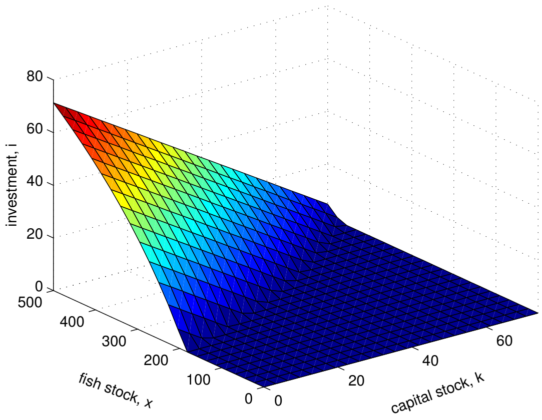

Figure 2 investment, i_t, without quota restriction

4. Results

Before presenting the optimal quota under multiannual quota we need to understand the characteristics of the optimal policy under annual quota. Because we assume that the EU knows how fishermen behave without quota restriction, we first show in Figures 1 and 2 harvest and investment decisions of fishermen as function of capital stock k and fish stock x, when the quota is not restrictive. Consider the harvest decision in Figure 1. First, we observe that harvest increases in fish stock x and capital stock k, which agrees with [31]. Second, as follows from the assumption that $h_t = 0$ if $x < \hat{x}$, we see that harvest is zero below $x = \hat{x} = 185.6$. Third, although harvest increases in capital stock k, each additional unit of k reduces the catch per unit of effort, $CPUE = h/E$. This explains the reduced increase in harvest as capital increases. Finally, when capital stock is at its maximum, $k = 74$, harvest increases linearly as fish stock goes from the open access level $\hat{x}$ to its maximum, $x = 460$. The steepness, which can also be observed to some extent at lower values of capital stock k, indicates that k is so high that each additional unit of fish stock can be harvested without losing efficiency, or reducing catch per unit of effort. Consider now the investment decision in Figure 2. The figure shows that investment increases in x and decreases in k. If $x < \hat{x}$, investment is zero because harvest is zero.

Figure 3 gives the optimal quota as a function of fish stock x and capital stock k. The goal of the quota is to steer both harvest and investment, which can be verified by fixing quota to a low level. The result is that both harvest and investment are reduced. To see how the quota deals with those tasks, consider the difference in optimal quota between low and high levels of k. At high capital stock, the quota restricts only harvest because investment is zero, whereas harvest is very high. At low capital stock, harvest is low, and even lower than the quota. However, as fish stock x increases, it becomes more attractive to stimulate investment so that fishermen can harvest more. Figure 4 shows for harvest that at high capital stock, fishermen are restricted by quota. While harvest is 330 kton at $x = M$ and $k \in [47, 74]$ in the unrestricted case, it is only 210 kton in the restricted case. At low capital stock, harvest is restricted by capital stock rather than quota. Investments in Figure 5 are very much affected by quota; the highest level of investment goes down from 70 kton without restriction to 12 kton with restriction.

4.1. Effect of multiannual quota

We now consider multiannual quota for a fixed quota period $f = 2, 3, 4, 5$ in Figures 6-9. Comparing low fish stock levels x to high levels, two observations can be made. First, at high fish stock levels, the quota declines with f. Second, at low fish stock levels, the quota increases with f. The intuition

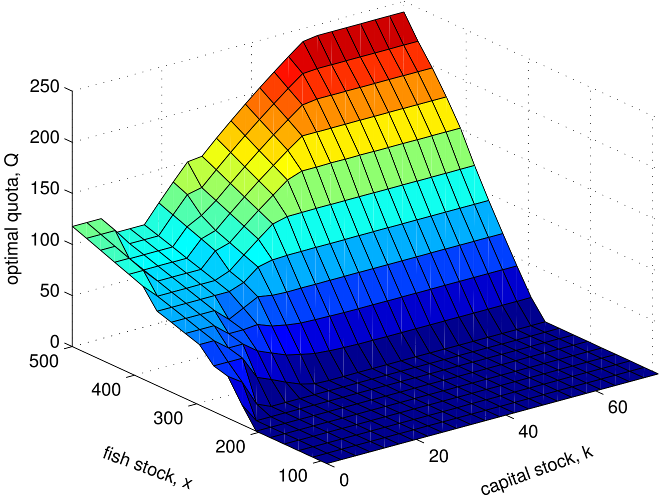

Figure 3 Optimal quota, Q, for each combination of fish stock, x, and capital stock, k

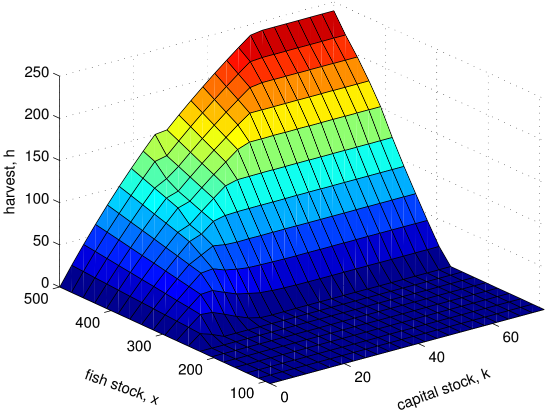

Figure 4 harvest, h_t, with quota restriction

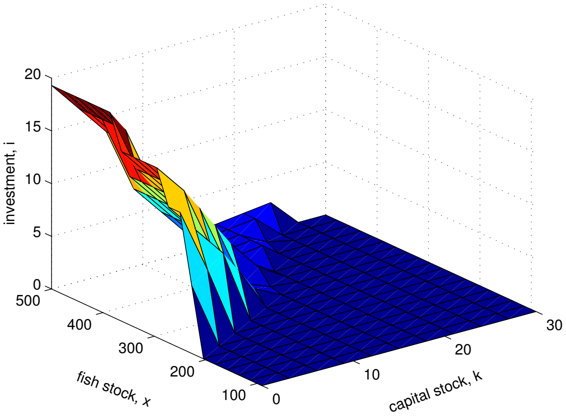

Figure 5 investment, i_t, with quota restriction

behind this result is as follows. When fish stock is high, we know from the density dependent growth function that growth is low, as well as stochastic. In order to maintain a sustainable stock in all future periods, the EU needs to be conservative when assigning a quota. This conservative behaviour is enforced as the quota is fixed for a longer period of time. With an increasing fixed quota period f, the EU has to anticipate fish stock over a longer period of time. This means that for low growth, uncertain stock growth and fixed quota, the optimal policy decreases in f. The reverse holds when we consider low fish stock levels. Here the EU knows that growth is high, so if a positive quota is assigned today the fish stock will recuperate in the future. We therefore observe a positive quota that increases in f and a quota that becomes positive at lower levels of fish stock as f increases. Finally, although the optimal quota clearly depends on fixed quota period f, harvest and investment are largely unaffected.

The dynamic behaviour of the model can be studied with a forward simulation. It allows studying policies and their fluctuations over time. Using optimal quota as input, we first consider a sample path and demonstrate differences in quota fluctuation for different values of fixed quota period f.

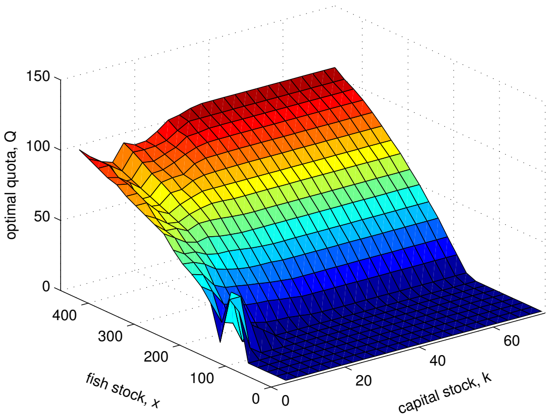

Figure 6 Optimal quota, Q, for $f = 2$

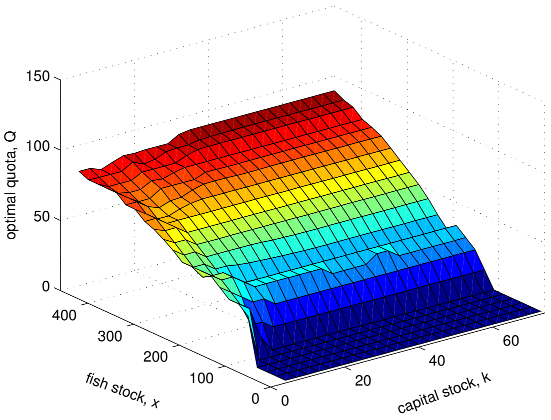

Figure 7 Optimal quota, Q, for $f = 3$

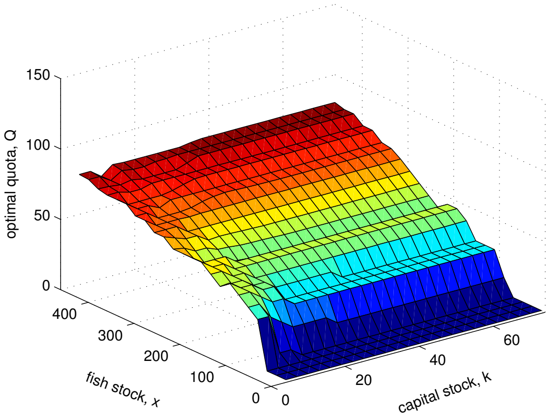

Figure 8 Optimal quota, Q, for $f = 4$

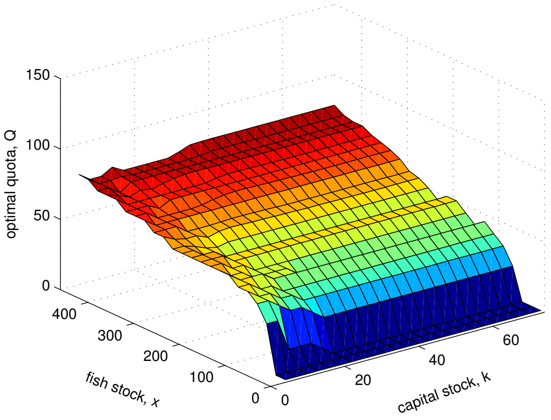

Figure 9 Optimal quota, Q, for $f = 5$

We then consider an average path of a sample size of 100,000 in order to study long term stability of paths.

Figure 10 shows for a sample size of 1 and a period of 100 years the sample path of quota for $f = 1, 3, 5$. Considering the research question whether quota fluctuation decreases under multiannual quota, we first look at annual quota. We observe strong fluctuation in annual quota, with quota values ranging between $Q = 52.8$ and $Q = 68.7$. Comparing this policy with multiannual quota for periods $f = 3$ and $f = 5$, we see that fixing quota for multiple years leads to less fluctuation; for a period of $f = 3$, quota values range between $Q = 59.7$ and $Q = 68.1$, and for $f = 5$ between $Q = 61.2$ and $Q = 66.2$. Three factors contribute to this decrease in quota fluctuation. The EU (i) accounts for uncertainty in fish stock growth, (ii) has to anticipate future fish stock over a longer period of time and (iii) deals with a longer recovery period of fish stock, i.e. the quota is adjusted less to extremely low fish stock values than what we observe under annual quota adjustment. This result is confirmed for long term averages of quota for fixed quota periods $f = 1, 3, 5$. Quota are $Q_t \in \{61.8, 62.8, 63\}$, with corresponding reduced average standard deviation $\bar{\sigma} \in \{0.1, 0.048, 0.047\}$. Figure 11 shows that, given initial stock values $x_0 = 250$ and $k_0 = 10$, average long term quota increases slightly in f. The time to reach the long term average, however, increases in f, which is a consequence of decreasing flexibility in quota adjustment. Note that these long term averages are

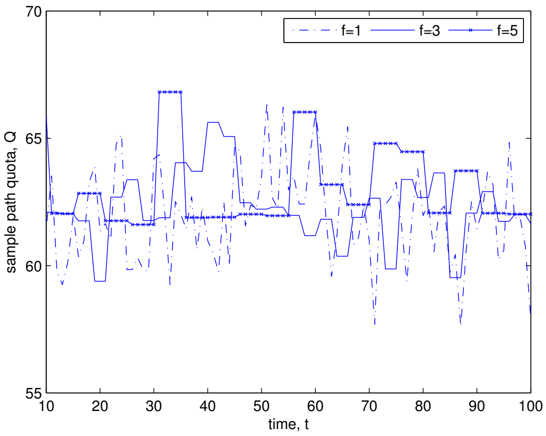

Figure 10 Sample path of quota, Q_t, for $f = 1, 3, 5$

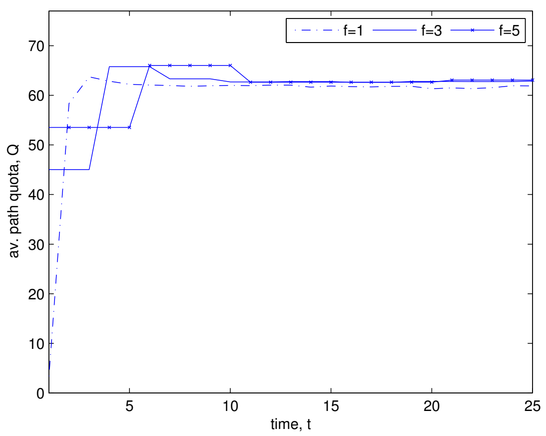

Figure 11 Average sample of quota, Q_t, for $f = 1, 3, 5$

reached for all combinations of x_0, k_0, and, the further away these initial values are from long term averages, the longer it takes to arrive there.

It can be concluded that annual quota leads to strong fluctuation and that multiannual quota indeed reduces this fluctuation. The trade-off is that, as the fixed quota period increases, it takes longer to reach a stable long term average.

4.2. Effect of management costs

To investigate the question whether a reduction in annual management costs offsets reduced flexibility in quota adjustment, we look at the effect of management costs on the value of the fishery. Figure 12 shows value function V_t from Equation (6), for fixed quota periods $f = 1, 2, 3, 4, 5$, where fish stock and capital stock are fixed at values $x_t = 250$ and $k_t = 9.7$. Alternative values produce a similar shape of V_t. The straight line represents the system of reduced annual management costs, where social benefits π_t are a function of c_{mc}/f. This is compared with the dotted line, the case in which these costs do not reduce in f; π_t is a function of c_{mc}.

The figure shows that when annual management costs are constant in f, value V_t only increases between $f = 1$ and $f = 2$. Whereas in the case that management costs reduce in f, the value of the fishery increases. This is explained by higher quota, harvest and revenues as follows. First, we have seen in Figure 11 that quota increases in f. On one hand, myopic harvest behavior of fishermen explains that higher quota is followed by higher harvests and thereby higher revenues. On the other hand, even though the quota increases, this harvest behavior prevents fishermen from being able to meet the effort requirement $\hat{E}_t$, so that on average harvest is more often restricted by capital stock than by quota. Second, higher effort and higher investment under multiannual quota results in an increase in effort costs, crew costs and investment costs. The increase in costs, however, is less than the reduction in management costs. Finally, management costs directly enter the social benefits function, so that a reduction directly influences social benefits.

We can conclude that under multiannual quota, reduced flexibility in quota adjustment is offset by a reduction in annual management costs. The value of the fishery increases while fluctuation of quota decreases. Furthermore, we show that it is important to account for management costs, irrespective of whether they are relatively small or large to benefits, because they directly influence the value of the fishery.

4.3. Capital volatility and overcapacity

So far we have shown that multiannual quota reduces quota volatility. Given conflicting objectives of the EU and fishermen, a follow-up question is whether a reduction in quota volatility also leads

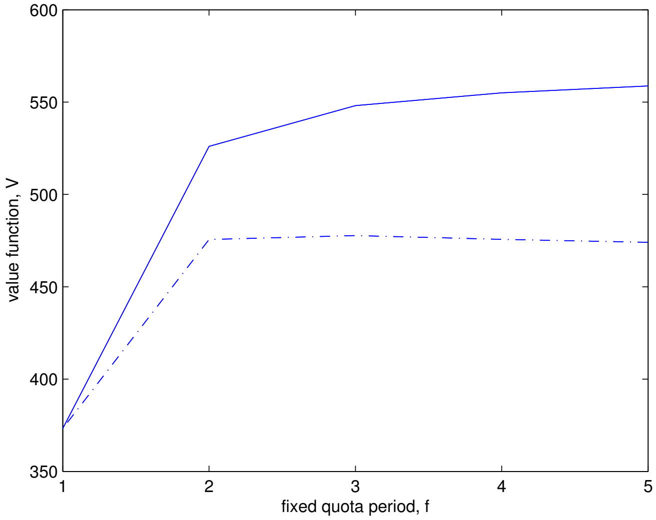

Figure 12 Value function, V_t, given $x_t = 250$ and $k_t = 9.7$, for $f = 1, 2, 3, 4, 5$, compared between a system with reduced annual management costs, c_{mc}/f, straight line, and a system with fixed annual management costs, c_{mc}, dotted line

to less volatile capital adjustment and less overcapacity for fishermen. To investigate this question, we focus on the restrictiveness of capital stock versus that of quota. Figures 13 and 14 present a 25 year sample path of fishermen's decisions, for a fixed quota period of $f = 3$.

Figure 13 shows the sample path of harvest h_t. Because of myopic behavior of fishermen, it appears that harvest is either restricted by quota Q_t, or by the maximum possible harvest given the available capital stock, $\tilde{h}_t = x_t(1 - e^{-qk_t})$. This phenomenon can be observed for any fixed quota period f. The sample path of investment i_t, in Figure 14, illustrates that the investment is positive when required effort $\hat{E}_t$ is greater than the depreciated capital stock $(1-\gamma)k_t$. Because level $h_t = (x_t - \hat{x})^+$ is rarely lower than quota Q_t, fishermen will always try to fully harvest Q_t. Their investment in period t, however, only becomes available in period $t+1$. Therefore, the current capital stock does not always meet the desired capacity.

To investigate whether overcapacity is reduced under multiannual quota, Figure 15 presents the long term average value of overcapacity, defined as k_t minus E_t, for varying fixed quota periods f. Although overcapacity is relatively small compared to capital stock k_t and effort E_t, Figure 14 shows that overcapacity increases between annual quota $f = 1$ and bi-annual quota $f = 2$. Even though the quota increases in f, fishermen are lead by their myopic behavior. The result is that on average, for fixed period $f = 2$, their capital stock is more often restricting than quota. This is enforced as the fixed quota period becomes longer, so that the observed overcapacity increases in f.

With this we conclude that even though the quota fluctuates less under multiannual quota, (i) capital adjustment is volatile due to fishermen's myopic behavior, and (ii) overcapacity increases in f.

5. Sensitivity analysis

To test robustness of the model and to explore implications of alterations in parameter values, we conducted a sensitivity analysis. Table 1 shows the effect of changes in economic and biological parameters on long term average values of quota, Q_t, and social benefits, π_t. We measure this for fixed quota periods $f = 1, 3, 5$.

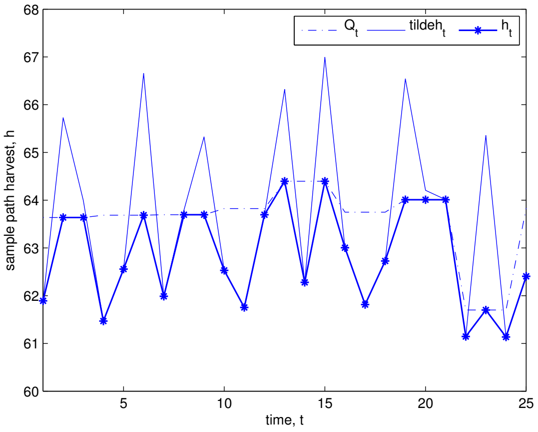

Figure 13 Sample path of harvest, h_t, for $f = 3$, with restrictions by quota, Q_t, and the maximum possible harvest given capital stock, $\tilde{h}_t$

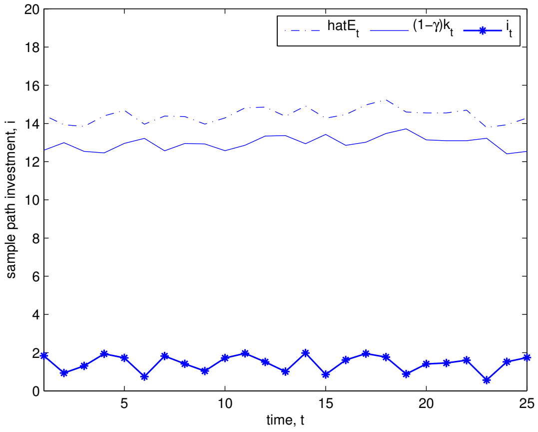

Figure 14 Sample path of investment, i_t, for $f = 3$, with restrictions by required effort, $\hat{E}_t$, and available capital stock, $(1-\gamma)k_t$

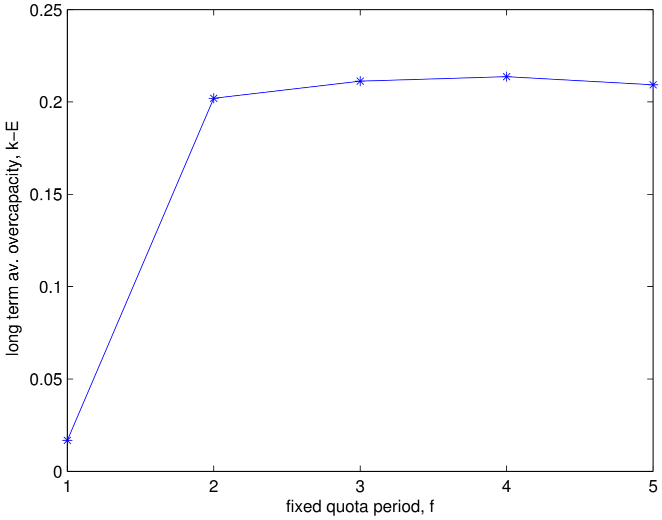

Figure 15 Long term average value of overcapacity, $k_t - E_t$, for $f = 1, 2, 3, 4, 5$

The baseline, in row 1, holds values that result from the illustrated case of North Sea plaice. With respect to the long term average value of quota in column 1, it has been shown that the increase of quota Q_t in fixed quota period f is a consequence of the combined effect of having to account for uncertainty in fish stock growth and anticipating future fish stock over a longer period of time. In addition, multiannual quota allows fish stock to grow and to recover faster than under annual quota. They are therefore not adjusted to levels as low as under annual quota and the long term average value increases. With respect to long term average values of social benefits in column 3, the increase of social benefits π_t in fixed quota period f has been shown to be a result from the reduction in annual management costs.

Do baseline results hold when parameter values change? In rows 2, 3 and 4 costs per unit of revenue, which represent crew costs, c_R, effort, c_E and investment, c_i, were each increased by 50%. Long term average values of quota and social benefits increase in f, but they are lower than in

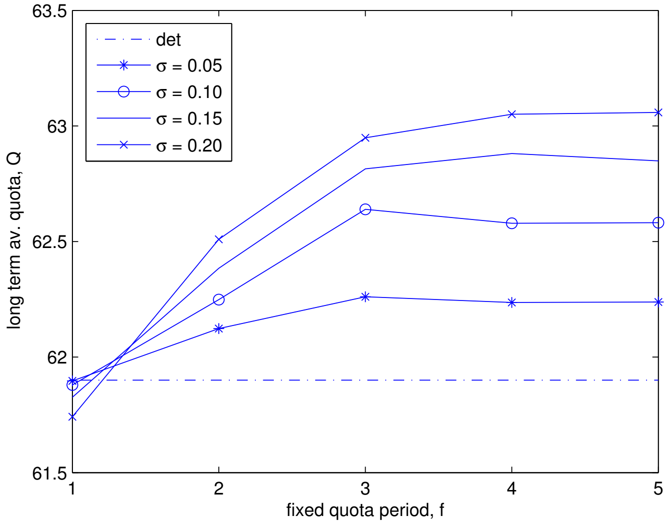

Figure 16 Effect of different values of σ on long term average quota, Q_t, for $f = 1, 2, 3, 4, 5$

the baseline, where the extent of reduction depends on the proportion of each cost factor in social benefits. Effort costs $c_E E_t$ in fact make up for the largest proportion of social benefits in the baseline. This explains why an increase in c_E has a larger downward impact on quota than an increase of c_R and c_i.

The impact of management costs on decisions, and on corresponding costs, is relatively small in the baseline. Management costs directly enter into social benefits, which increase in fixed quota period f due to the annual reduction. Does this hold when management costs are higher? Literature has shown that management costs may range between 2.5% and 25% of harvest value. In order to capture the effect of much higher management costs on quota Q_t and social benefits π_t, we consider in row 5 of Table 1 a value for c_{mc} that is twice as high as in the baseline. Similar to the baseline, it shows that the long term average quota is almost not affected by a management costs c_{mc} that is twice as high as in the baseline. This is enhanced as c_{mc} increases.

Finally, in row 6 a higher intrinsic growth rate of fish stock, $r = 0.9$, is considered. Relative to the baseline, a higher growth rate allows fish stock to recover faster, with the result that the long term average quota increases.

Figure 16 shows long term average quota for different levels of stochasticity of fish stock growth, for $f = 1, 2, 3, 4, 5$. We consider $\sigma = \{0.05, 0.10, 0.15, 0.20\}$, as well as the deterministic case. The dotted line represents quota Q_t in the deterministic setting, where the quota does not depend on the fixed quota period f. If $f = 1$, the EU only accounts for uncertainty in growth, which leads to conservative decisions and thus a lower long term average quota as uncertainty increases. If $f > 2$, the EU also has to anticipate future fish stock over a longer period of time. In terms of a sample path like in Figure 10, the effect of having to account for both uncertainty and a fixed quota period leads to even fewer low values of quota. In terms of the long term average, as in Figure 11, the quota increases because it does not have to be adjusted to levels as low as under annual quota. And this is enhanced as σ increases.

The average path of quota shows that with an increase in the fixed quota period, the long term average tends to a higher value than the average of the annual quota adjustment. This leads to an increase in the long term average value of multiannual quota itself.

Table 1 Effect of changes in economic and biological parameters on quota, Q_t, and social benefits, π_t, for $f = 1, 3, 5$

Parameter changes	f	Quota, Q_t	99% CI	Social benefits, π_t	99% CI
Baseline	1	61.83	$[61.80, 61.85]$	27.09	$[27.06, 27.12]$
	3	62.85	$[62.81, 62.88]$	30.54	$[30.51, 30.56]$
	5	62.89	$[62.86, 62.91]$	31.21	$[31.19, 31.22]$
crew cost, c_R	1	52.79	$[52.60, 52.98]$	13.72	$[13.66, 13.77]$
	3	54.07	$[54.07, 54.09]$	17.22	$[17.19, 17.24]$
	5	53.87	$[53.85, 53.88]$	17.90	$[17.89, 17.92]$
effort cost, c_E	1	41.39	$[39.40, 43.36]$	7.52	$[6.83, 8.22]$
	3	41.75	$[41.26, 42.25]$	10.98	$[10.64, 11.32]$
	5	41.72	$[41.60, 41.84]$	11.69	$[11.43, 11.94]$
investment cost, c_i	1	61.78	$[61.75, 61.81]$	25.60	$[25.67, 25.64]$
	3	62.12	$[62.10, 62.14]$	29.05	$[29.02, 29.07]$
	5	62.40	$[62.38, 62.42]$	29.73	$[29.71, 29.75]$
management cost, c_{mc}	1	61.84	$[61.82, 61.86]$	21.82	$[21.79, 21.85]$
	3	62.79	$[62.69, 62.88]$	28.75	$[28.69, 28.80]$
	5	62.83	$[72.71, 62.95]$	30.14	$[30.08, 30.19]$
intrinsic growth rate, r	1	74.08	$[73.94, 74.22]$	23.48	$[31.82, 33.14]$
	3	74.91	$[74.87, 74.95]$	35.98	$[35.77, 36.19]$
	5	74.84	$[74.81, 74.87]$	36.67	$[36.54, 36.80]$

6. Discussion and conclusions

Uncertainty in fish stock growth provides an important challenge to decision-makers. Yearly revisions of fisheries policies lead to fluctuation in quota, which in turn results in overcapacity for fishermen. It is therefore unlikely that the current system of annual quota is optimal. Another phenomenon in yearly quota adjustment is the high management costs involved. Therefore, decision-makers are developing new policies with which they hope to improve both biological sustainability and social benefits.

The EU, for example, has proposed a system of multiannual quota for North Sea fish species. An incentive of this system is to reduce annual fluctuation in quota, so that fishermen will be subject to less capital volatility and less overcapacity. In addition, it reduces annual management costs as fewer meetings are required between policy makers and scientists. It remains unclear, however, whether this policy, compared to annual quota, indeed reduces quota volatility and increases the value of the fishery. We investigated these questions with a bi-level Stochastic Dynamic Programming model.

Our results suggest that multiannual quota leads to less fluctuation in quota and that reduced flexibility in quota adjustment is offset by a reduction in annual management costs. Three factors contribute to reduced quota volatility under multiannual quota. First, the EU accounts for uncertainty in fish stock growth. Second, the EU anticipates future fish stock over a longer period of time and third, fish stock has a longer recovery period. With and increasing fixed quota period, it takes longer to reach a steady long term average quota. Therefore, the long term average quota increases slightly.

An interesting aspect of reduced quota volatility is that it contrasts with the conventional expectation that a more restrictive system leads to more extreme adjustments. These extreme adjustments are necessary in order to prevent the fish stock from falling below sustainable levels [29, 22]. The finding also deviates from the consequence of multiannual quota shown in [20]. There, multiannual quota is more likely to speed-up fish stock recovery than annual quota. Quota in our model, as mechanism to steer harvest and investment, becomes steady once fish stock and capital stock have become steady. A longer fixed quota period implies more time to reach a steady long term average quota. That way, it also takes longer to reach steady long term average values of fish stock and capital stock.

According to our study, reduction in annual management costs under multiannual quota hardly affects decisions of EU and fishermen. Due to the little impact on revenues and costs, the reduction directly increases social benefits and thereby increases the value of the fishery. The EU generates the highest value when the quota is fixed for the largest fixed quota period considered in this study, which is five years. This comes, however, at the cost of more overcapacity of fishermen. The long term average value of overcapacity increases wih the fixed quota period, due to the myopic behavior of fishermen in the model. This gives that there will always be a discrepancy between available capital and required capital. While it has been said that management costs do not need to be accounted for because they are relatively small to benefits [1], we find that it is important to account for them. Irrespective of whether they are relatively small or large, management costs directly influence social benefits. This indicates that a policy is only optimal when the benefit maximizing decision-maker accounts for these costs.

Naturally, the reported results are subject to a number of assumptions. Although the assumption of myopic behavior may be considered a simplicification, it is not far off from true fishermen behavior according to [12] and [9]. The used maximum on the fixed quota period of five years suffices to address the research questions on fluctuating quota and management costs. It may be unlikely that the EU will opt for a larger fixed quota period, even if the value of the fishery is higher. It is further assumed that the source of uncertainty comes from fish stock growth alone. This assumption ignores that the observed stock may not be the true stock. This is another, potentially more important, source of uncertainty.

With this study, we have shown that the EU can reduce quota volatility and improve the value of the fishery with multiannual quota. Overcapacity, however, increases, which indicates that conflicting objectives of the EU and fishermen cannot be solved with this policy. In future work, the model will be extended to account for alternative forms of fishermen behavior and different management schemes. A deeper understanding may help to find ways to reduce overcapacity.

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