Individual quotas, fishing effort allocation, and over-quota discarding in mixed fisheries

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Many fisheries are managed by total allowable catches (TACs) and a substantial part by individual quotas. Such output management has not been successful in mixed fisheries when fishers continue to fish while discarding marketable fish. We analyse the effects of individual quotas on spatial and temporal effort allocation and over-quota discarding in a multispecies fishery. Using a spatially explicit dynamic-state variable model, the optimal fishing strategy of fishers constrained by annual individual quotas, facing uncertainty in catch rates, is studied. Individual fishers will move away from areas with high catches of the restricted quota species and, depending on the cost of fishing, will stop fishing in certain periods of the year. Individual vessels will discard marketable fish, but only after their individual quota for the species under consideration has been reached. These results are in line with observations on effort allocation and discarding of marketable fish, both over-quota discarding and highgrading, by the Dutch beam-trawl fleet. The models we present can be used to predict the outcomes of management and are therefore a useful tool for fisheries scientists and managers.

Keywords: behavioural responses, dynamic-state variable modelling, fishing effort, fleet dynamics, quota regulations.

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Introduction

Output management in mixed fisheries through total allowable catches (TACs) is not generally successful if fishers continue to fish and to discard marketable fish (over-quota discarding; Daan, 1997; Pascoe, 1997; Rijnsdorp *et al.*, 2007). Only if vessels operate under an observer programme where over-quota catches are recorded and penalized will fishers be forced to redirect fishing effort away from the concentrations of the limiting resource entirely (Branch and Hilborn, 2008).

In the EU, many fisheries are managed by annual TACs without a legal restriction on discarding (Holden, 1994). Although qualitative information on over-quota discarding does exist (Rijnsdorp *et al.*, 2006), the quantities and age structure of discards remain unknown for many fisheries. However, over-quota discarding may have severe implications for estimates of stock biomass and fishing mortality (Cotter *et al.*, 2004), in particular where discarding applies to certain age classes (the less valuable market categories).

Bottom-trawl fleets generally engage in mixed fisheries, where a multitude of species contribute to the output of the fishery. As these species differ in habitat requirements and may differ in their seasonal migration pattern, the species composition of the catches will vary in space and time. A heterogeneity in species composition offers fishers the opportunity to influence the species composition of their catch, at least to some extent, by redistributing their fishing effort to optimize profits within the constraints set by management (Hutton *et al.*, 2004; Branch and Hilborn, 2008; Gillis *et al.*, 2008).

The North Sea flatfish fishery is a typical example of a TAC-regulated mixed fishery, with catches including the flatfish species sole (*Solea solea*), plaice (*Pleuronectes platessa*), turbot (*Psetta maxima*), and brill (*Scophthalmus rhombus*), each with different seasonal availability patterns (Rijnsdorp *et al.*, 2006; Poos and Rijnsdorp, 2007a) and prices. Sole and plaice dominate the landings and can be considered to be the main target species (Gillis *et al.*, 2008). Adult plaice migrate from the southern spawning grounds to the northern feeding grounds in spring, where they stay until the return migration in autumn (Rijnsdorp and Pastoors, 1995; Hunter *et al.*, 2004; Bolle *et al.*, 2005). On the other hand, sole follow an east-to-west migration cycle that overlaps with the winter distribution of plaice (de Veen, 1967, 1978). Sole is the most valuable species, contributing most to the landings expressed in monetary value, and plaice is the second most valuable (Gillis *et al.*, 2008).

The TACs for these stocks are set annually after political negotiations, based on stock assessments produced by ICES (Daan, 1997). The TAC is subsequently subdivided across EU Member States using a fixed allocation rule based on historical catches and special provisions for areas heavily dependent on fishing (Holden, 1994). In the Netherlands, the TACs are divided into individually transferable quotas (ITQs), owned by fishing companies (Salz, 1996). ITQs potentially reduce competition and excess investment, while fostering economic efficiency (Squires *et al.*, 1998).

Many studies exist in which the effects of individual quotas on discarding are considered (Vestergaard, 1996; Turner, 1997; Herrera, 2005). However, these studies often ignore the flexibility that individual fishers have in modifying the catch composition by changing their fishing pattern in space and time. In this study, we explore the effects of annual individual quotas on discarding, explicitly accounting for spatio-temporal effort allocation, adding a basic dimension of fleet dynamics to the understanding of discarding behaviour.

Dynamic-state variable models offer a powerful tool to study this behavioural flexibility because they allow mixing the time-scales between choices and constraints (Clark and Mangel, 2000). Previous studies on fleet dynamics using dynamic-state variable models showed that single-species trip quota can lead to highgrading when only the most valuable component of the catch is taken into account (Gillis *et al.*, 1995). This single-species approach made use of several market categories, differing in value. Within each haul, the choice made by the individual fisher for each trawl was to discard or to retain the entire catch of each market category. Another study used a dynamic-state variable model to optimize targeting decisions made by bottom trawlers under management-imposed trip limits on landings of each target species (Babcock and Pikitch, 2000). The model predicted that the vessel would fish a single strategy exclusively without trip limits, but would switch between strategies several times under restrictive trip limits. Although that study allowed changes in effort allocation resulting from quota constraints, no discarding was permitted in the model.

We develop a dynamic-state variable model to study the effect of restrictive quotas on the spatio-temporal effort allocation and discarding of marketable fish in the beam-trawl fishery for sole and plaice. It is assumed that a fisher will maximize the economic pay-offs (Gordon, 1953, 1954), analogous to optimal foraging theory in animal behaviour (Stephens and Krebs, 1986; Krebs and Davies, 1984), and will choose the strategy that maximizes annual net revenue given the constraints set by the quota. The strategy consists of a combination of (i) the choice whether or not to go fishing, (ii) the choice of fishing areas with different expected catch rates, and (iii) the choice whether or not to discard the over-quota part of the catch. Choices by month are calculated against annual quota constraints. This study extends the dynamic-state variable models on discarding (Gillis *et al.*, 1995; Babcock and Pikitch, 2000) by explicitly taking into account the flexibility of discarding and effort allocation in space and time.

Methods

Model description

A dynamic-state variable model (Clark and Mangel, 2000) is used to evaluate the optimal strategy for a fishing vessel under two annual landing quotas, mimicking the mixed fisheries for sole and plaice in the North Sea. Dynamic-state variable models assume that optimal fishing behaviour can be calculated under the assumption that each individual is a utility maximizer. Although many other incentives may play a role in fisher behaviour, there is some empirical evidence for profit as the metric of utility (Robinson and Pascoe, 1998). Dynamic-state variable models allow combining the time-scales of short-term choices and long-term constraints such as fishers facing an annual quota system but making daily, weekly, or monthly decisions on where to fish and which fish to keep on board (Clark and Mangel, 2000). The individual vessels in the model may be constrained by their quota for the individual species and will respond by changing their fishing pattern in terms of (i) the number of fishing trips, (ii) the choice of fishing areas, and (iii) the choice to discard the over-quota part of their catch.

The problem for the individual is therefore to optimize the utility function Φ, in this case the net revenue at the end of year T. The net revenue is based on total landings for the two species, L_1 and L_2, total fishing effort and travel time, E, and their respective prices, p_1 and p_2, and variable costs, p_e, taking into account the total fine D for a vessel exceeding its individual quota for either species:

$$\Phi(L_1, L_2, E) = L_1 p_1 + L_2 p_2 - D - E p_e. \quad (1)$$

The total fine is calculated as a function of the fine d_1, d_2 per unit of landings, the quotas q_1, q_2, and the landings:

$$D = \begin{cases} 0 & \text{if } L_1 \le q_1 \text{ and } L_2 \le q_2 \\ d_1(L_1 - q_1) & \text{if } L_1 > q_1 \text{ and } L_2 \le q_2 \\ d_2(L_2 - q_2) & \text{if } L_1 \le q_1 \text{ and } L_2 > q_2 \\ d_1(L_1 - q_1) + d_2(L_2 - q_2) & \text{if } L_1 > q_1 \text{ and } L_2 > q_2 \end{cases}. \quad (2)$$

In our model, time passes in monthly steps (t). The expected net revenue at the end of the year needs to be linked to the choices in the preceding months. This is done using the value function, which is the maximum expected net revenue between month t and the end of year T, expressed as $F(L_1, L_2, E, t)$. At the end of the year, this is by definition equal to the net revenue function $[F(L_1, L_2, E, T) = \Phi]$. In the months preceding T, the function depends on the expected net revenue consequences $V_{ijk}(L_1, L_2, E, t)$ of visiting an area i and discarding an excess of j tonnes of the catch of species 1 and discarding an excess of k tonnes of the catch of species 2:

$$V_{ijk}(L_1, L_2, E, t) = \sum_{l_1} \sum_{l_2} \lambda_{ij}(l_1, t) \lambda_{ik}(l_2, t) F(L_1 + l_1, L_2 + l_2, E + e_i, t + 1). \quad (3)$$

In Equation (3), $\lambda_{ik}(l_1, t)$ is the probability that a vessel during a specific time-step (month) will land l_1 tonnes of fish of species 1, given a visit to area i and a choice to discard everything more than j. Likewise, $\lambda_{ik}(l_2, t)$ is the probability that a vessel during a specific time-step will land l_2 tonnes of fish of species 2, given a visit to area i and a choice to discard everything more than k. The parameter e_i is the effort needed to visit area i.

The probabilities $\lambda_{ij}(l_1, t)$ and $\lambda_{ik}(l_2, t)$ can be seen as resulting from a two-stage process. First, the probability of a catch is calculated using discretized normal distributions with means μ_{1it}, μ_{2it}, and standard deviations σ_1, σ_2, respectively, for the two species. The reason for choosing a normal distribution is that although the statistical distribution of catches per haul may not be normal (e.g. lognormal), the sum of the large number of catches per month will approximate a normal distribution. Then, the probability for the actual landings is adjusted by assuming that the catches more than j, k, are discarded. The probability of landings more than these discarding choices j and k are set to zero.

Hence $\lambda_{ij}(l_1, t)$ has the following cumulative distribution function:

$$\lambda_{ij}(l_1 \le \chi, t) = f(\chi; \mu_{1it}, \sigma_1, j) = \begin{cases} 0 & \text{for } \chi < 0 \\ \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\infty}^{\chi} e^{-(x-\mu_{1it})^2/2\sigma_1^2}\,dx & \text{for } 0 \le \chi < j \\ 1 & \text{for } \chi \ge j, \end{cases} \quad (4)$$

and $\lambda_{kj}(l_2, t)$ is calculated in a similar manner. Finally, the stochastic dynamic programming equation that provides the optimal choice for the areas to visit and the discarding of marketable fish is

$$F(L_1, L_2, E, t) = \max_{ijk}\{V_{ijk}(L_1, L_2, E, t)\}, \quad (5)$$

and calculated in a backward iteration because of the recursive nature of $F(L_1, L_2, E, t)$, which depends on V_{ijk} (L_1, L_2, E, t), in turn depending on $F(L_1+l_1, L_2+l_2, E+e, t+1)$. The optimal fishing strategy is an array $H(L_1, L_2, E, t)$ defining the optimal fishing strategy with respect to i, j, and k in each time-step, given the state variables L_1, L_2, E. After the backward iteration, the expected distribution of observed decisions can be determined by the forward iteration. This simulates a number of individuals who choose the optimal path, defined by the optimal strategy, given the stochastic nature of the catches.

The model is written in C++, used in a library that is part of the FLR suite (Kell *et al.*, 2007) of R (R Development Core Team, 2007). The OpenMP paradigm is used in the C++ part of the model to allow parallel computation of the backward iteration on computers with multiple processors (Chapman *et al.*, 2007). The probability distributions of the catches for the two species are discretized into 27 bins for each time-step, resulting in 324 discrete states in total for each of the two species. For each of the three areas i, the amount of discarding options j, k is equal to the number of bins per monthly time-step used to discretize the catches. Hence, the discarded fraction of the catch in a single time-step can take a range of values between [0, 1]. Staying in port is defined as an additional area, with a zero catch for the two species and no effort. The model was run on an eight-core desktop PC, and a single run (backward and forward calculations for a single set of quota) took <10 min.

Model parameterization

The Dutch large beam-trawl fleet that is used to parameterize the model described above has been described in detail by Quirijns *et al.* (2008). The spatial distribution of the two resources in the model mimics the North Sea situation. Three different areas are assumed: (i) a northern area (central North Sea), which is part of the summer feeding grounds of plaice with high average catches of plaice (30 t month^{-1}) and low sole catches (1 t month^{-1}); (ii) a central area with intermediate catches for both species (20 t month^{-1} of plaice and 4 t month^{-1} of sole); (iii) a southern area (southern North Sea) with low catches of plaice and high catches of sole (8 t month^{-1} of plaice, 6 t month^{-1} of sole; Figure 1). The market prices used in the model are assumed independent of the total landings and are an approximation of the values observed in the field. Prices differ between species, with the typical first sale price for sole and plaice being €8 per kg and €2 per kg, respectively.

To address the effects of migration of plaice on effort allocation and discarding choices, two different resource distribution scenarios are used. The first assumes a constant mean and variance of the catch rates in the areas over time. The second assumes seasonally varying catch rates for plaice in the northern and the southern area (Figure 1, Table 1), reflecting plaice migration between southern spawning grounds in winter and northern feeding grounds in summer. Sole migrate along a latitudinal axis, and therefore within areas, rather than between areas. The standard deviations of the catch rates used in the model are taken from a generalized linear model of the monthly catch rates in the three areas between 2001 and 2005. The model assumes normally distributed catch rates with homogenous variance among the areas. The standard deviation for plaice and sole is estimated to be 5.6 and 2.7 t, respectively.

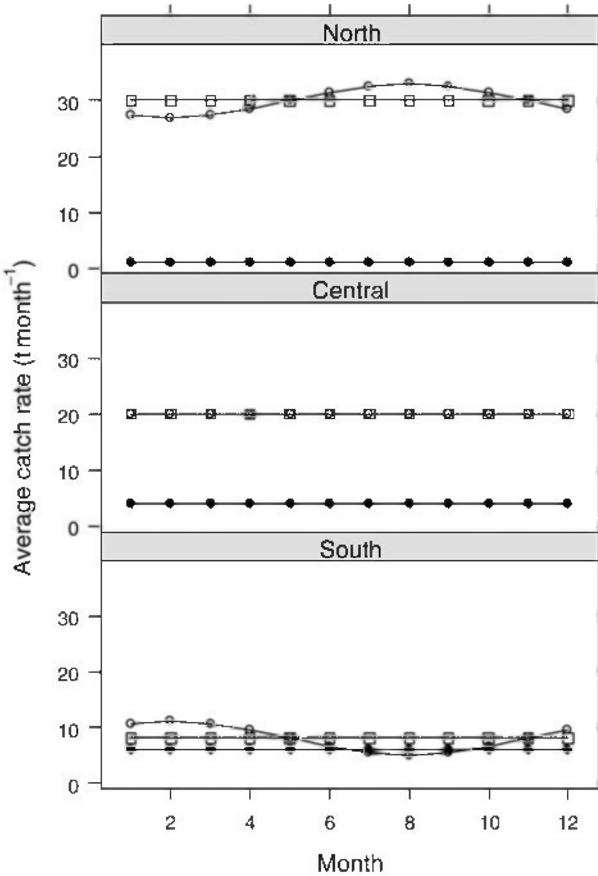

Figure 1. Average monthly catch rate of sole (black dots) and plaice in three areas assuming constant spatial distribution (open squares) and seasonal migration between spawning and feeding grounds (open circles).

The unit of effort used in the model is a day at sea, consisting of both fishing time and travel time. Independent of the chosen area, fishing time is fixed at 14 d. Travel time, however, differs between areas and is 0, 2, and 4 d for the southern, central, and northern areas, respectively. Hence, fishing in the southern area requires 14 d at sea per month, in the central area requires 16 d at sea per month, and in the northern area requires 18 d at sea per month. These values can be interpreted as the sum of the effort from three trips within a month because the average trip length in the beam-trawl fishery is 5 d, with trips in the north being longer. In the model, it is not possible for a vessel to switch between areas within a single time-step. Hence, only one area

Table 1. Resource distribution in the model as characterized by μ_{1it} (sole) and μ_{2it} (plaice) for the three areas in the different months t.

	Spatial variation		Spatial and seasonal variation	
Area	**Sole**	**Plaice**	**Sole**	**Plaice**
North	$\mu_{11t} = 1$	$\mu_{21t} = 30$	$\mu_{11t} = 1$	$\mu_{21t} = 30 + 3\sin(2\pi(t - 5)/12)$
Central	$\mu_{12t} = 4$	$\mu_{22t} = 20$	$\mu_{12t} = 4$	$\mu_{22t} = 20$
South	$\mu_{13t} = 6$	$\mu_{23t} = 8$	$\mu_{13t} = 6$	$\mu_{23t} = 8 + 3\sin(2\pi(t + 1)/12)$

For only spatial variation in the resource distribution, all μ_{1it} and μ_{2it} are independent of t. For both spatial and seasonal variation, μ_{21t} and μ_{23t} are a sinusoid function of t, reflecting the north–south migration of adult plaice in the North Sea.

can be selected within a month. In the beam-trawl fleet, a considerable portion of the variable costs of fishing relate to fuel. As an example, in 2006, the average fuel price was €0.41 per litre, and the average fuel costs per day were ~€3500 (Taal *et al.*, 2007). Fuel costs make up as much as 55% of gross revenue (Taal *et al.*, 2007). To analyse the effects of the variable costs of effort on the dynamics of the system, we analyse scenarios with low variable costs of fishing (€3000 per day) and high variable costs of fishing (€3500 per day). The cost of discarding marketable fish is assumed to be negligible compared with the fishing operation. Discarding, when it happens, would be incorporated into the regular sorting procedure.

In the model, catches and landings of the two species comprise just one market category, but in reality, the fishery lands different size categories, which differ in price. Hence, the discarded marketable fish is likely to constitute the least valuable market category (Gillis *et al.*, 1995). In our model, we did not explore the effect of price differences on the discarding of marketable fish (highgrading).

The model is used to analyse the effects of restrictive quotas on spatio-temporal effort allocation and the discarding of marketable fish. We consider the effects of differences in costs of fishing and the migration of the resources in combination with restrictive plaice quotas only because North Sea flatfish fisheries have been more constrained by plaice quotas than by sole quotas since 1990 (Quirijns *et al.*, 2008). The model is run for 11 levels of plaice quota ranging between 25 and 400 t. For each run, forward iterations are made for a fleet of 180 vessels (the average fleet size in the period 1990–2004; Quirijns *et al.*, 2008). Within a run, all vessels have equal individual landing quotas. Each sole quota is set at 130 t, which cannot be exceeded by any vessel given the maximum sole catches in the simulations. The fine for exceeding the quota is set at twice the price of the two species, sufficiently high to prevent landings from exceeding the quota. Lower fines could result in an incentive for fishers to exceed their quota, but this is not explored in this study.

Data analysis

The outcomes of the model in terms of spatial distribution and discarding can be contrasted against field observations from two different sources.

The first source is the dataset of mandatory logbooks that each fishing vessel must hand into the authorities at the end of each fishing trip. These logbooks have information on the fishing effort distribution of the entire Dutch beam-trawl fleet with a spatial resolution of ICES rectangles (0.5° latitude and 1° longitude) and a temporal resolution of 1 week. Although the logbooks are primarily used for management purposes, data are made available for research. The data consist of: vessel code, engine power of the vessel, type of fishing gear, ICES rectangles visited, date, time, and harbour of departure, and date, time, and harbour of arrival. The entire dataset spans the period 1990–2007.

From the mandatory logbooks, the centre of gravity (mean) of the fishing effort on the latitudinal axis was calculated by month (Y). The monthly estimates are used as observations in a general linear model:

$$Y_i = \beta_0 m_i + \beta_1 M_i + \beta_2 M_i^2 + \varepsilon_i, \qquad (6)$$

where for the ith observation (Y_i), m_i is the month of the year (as a factor), M_i the time elapsed since January 1990, and ε_i is a normally distributed error term. In this way, the seasonal effect and long-term trends in the centre of gravity of the fleet can be disentangled.

The second data source is individual electronic logbooks on fishing effort and catches on a haul-by-haul basis, collected in a collaborative research programme with the fishing industry during 2003 and 2004. Those logbooks allowed for comments by the skippers on their decisions on a haul-by-haul basis. In all, 20 fishers added qualitative information to their haul-by-haul logbooks about factors influencing their fishing decisions, a total of 1029 fishing trips, of which 222 contained comments on fishing tactics and strategy.

The comments were categorized and scored according to several categories, one of which was the mentioning of "discarding of marketable fish". Other categories included mentioning of gear problems, searching behaviour, weather conditions, restrictive quota, and fish prices. Therefore, from this dataset, spatial and temporal patterns in the occurrence of discarding marketable fish can be quantified from a sample of the fleet. In addition, the reason for discarding marketable fish (restrictive quota, low prices) could be quantified.

Results

We discuss the model outcomes for four scenarios regarding (i) differences in availability of the two species as a consequence of fish migration, and (ii) the costs of fishing. First, we present model results for fixed spatial then for seasonally varying resource distributions. Within these scenarios, we describe the effects of the different levels of variable (fuel) costs.

Spatial variation in species availability

In the absence of migration, the expected net revenue would be independent of season. The location choice clearly changes with changing plaice quotas (Figure 2); high quotas lead to fishing in the central area, for both high and low costs. All catches of marketable fish can be landed and net revenue is largest. A reduction in plaice quota <250 t results in relocation of effort towards the southern area. This is because the southern area becomes more profitable than the central area because of the larger catches of

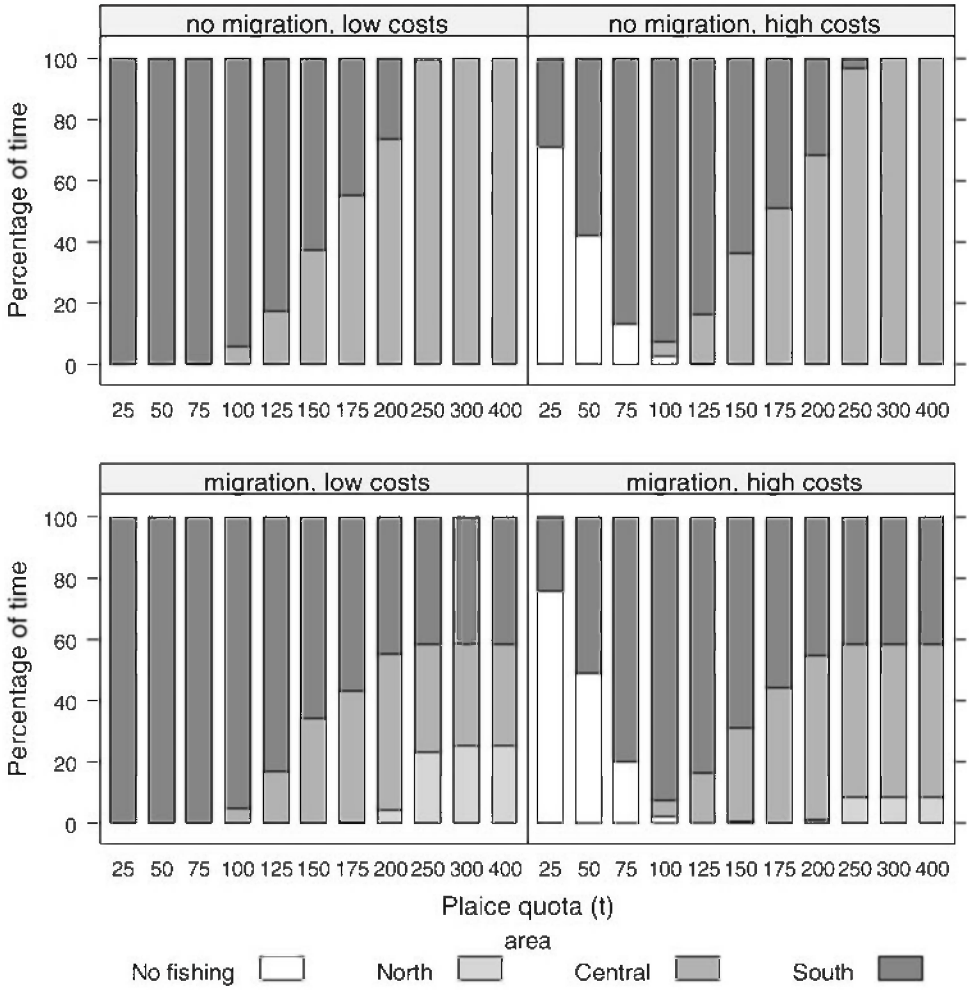

Figure 2. Modelled spatial allocation of fishing effort (percentage of time spent fishing in the different areas, or staying in port) for different levels of plaice quota assuming constant distribution of fish and low fishing costs (top left panel) and high fishing costs (top right panel), or assuming seasonally varying distribution of fish and low fishing costs (bottom left panel) and high fishing costs (bottom right panel).

sole and the lower costs. With very low quotas of plaice, the results differ for the two cost scenarios: in the low cost scenario, fishing in the southern area continues, but in the high-cost scenario, vessels spend less time at sea. In scenarios with low plaice quotas and high costs, fishing effort is allocated at the beginning of the year only (Figure 3).

The annual catch composition of the two species changes according to the reallocation of fishing effort (Figure 4). At levels of individual plaice quota >250 t, the quotas do not affect the catches or landings of either sole or plaice. Below 250 t plaice quota, the average annual catch of plaice decreases, following the level of the quotas, coinciding with a decrease in effort. As fishing effort is reallocated to the southern area with less travel time, sole catches increase. In this multispecies fishery, therefore, a decrease in plaice quota results in an increase in the apparent catchability of sole because the ratio of total sole catch over total fishing effort increases, at equal stock biomass.

At very low quotas of plaice, the effects of quota reductions differ between the two cost scenarios: at low costs, plaice catches become independent of the plaice quota, and all catches of marketable plaice that exceed the quota are discarded at the end of the year (Figure 5). The optimal strategy is to land all plaice caught until the vessel's quota is reached. Despite the vessel's low quota of plaice, fishing can continue on sole and still be profitable. Continued fishing also ensures high catches of sole. Alternatively, at high cost, very low quotas of plaice will result in a reduction in fishing effort at the end of the year, and hence very little discarding (Figure 5).

Owing to the stochasticity in the model, the time of year when the quotas are reached differs among fishers. This is caused by differences in cumulative fishing success resulting from the stochastic monthly catches.

Seasonal and spatial variations in resource availability

A seasonally changing distribution of fish has a clear effect on the distribution of fishing effort. With high quotas of plaice, fishing effort is allocated over all three areas (Figure 2). Effort allocation in the northern area is concentrated around month 8, when plaice availability peaks and catches are sufficiently high to offset the higher travel costs of visiting the area. The total amount of effort in the north depends on the cost per unit of effort, with the low cost scenario resulting in more effort being allocated in the area than under a high-cost scenario. Also, the southern area is visited at the beginning of the year when plaice availability

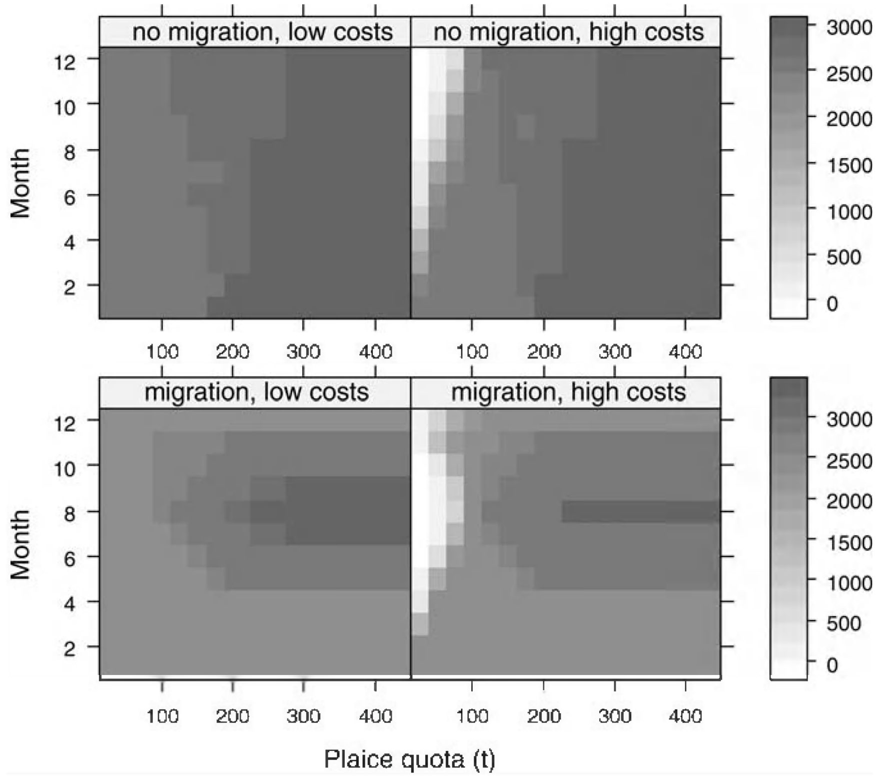

Figure 3. Modelled seasonal pattern in fishing effort (days at sea) for different levels of plaice quota assuming constant spatial distribution of fish and low fishing costs (top left panel) and high fishing costs (top right panel), or assuming seasonal varying distribution patterns and low fishing costs (bottom left panel) and high fishing costs (bottom right panel).

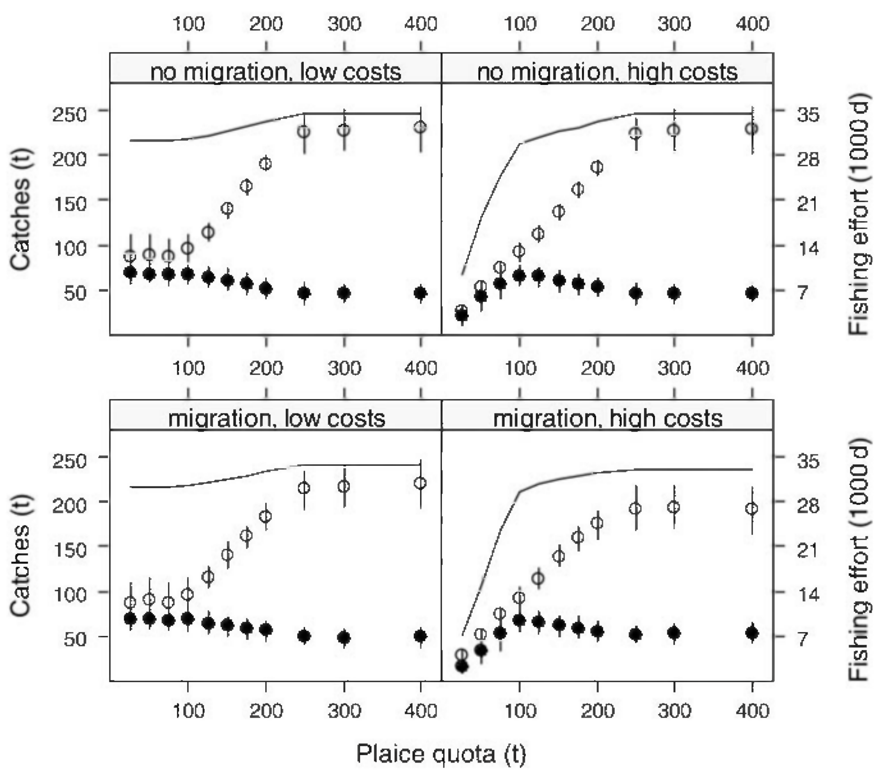

Figure 4. Modelled average annual catch per vessel of sole (black dots) and plaice (open circles) and fishing effort of the total fleet (line) at different levels of individual plaice quota, assuming a constant spatial distribution of fish and low fishing cost (top left panel) and high fishing costs (top right panel), or assuming seasonally varying distribution patterns and low costs per unit of effort (bottom left panel) and high costs per unit of area (bottom right panel). Error bars of the annual catches represent the 10 and 90% quantiles.

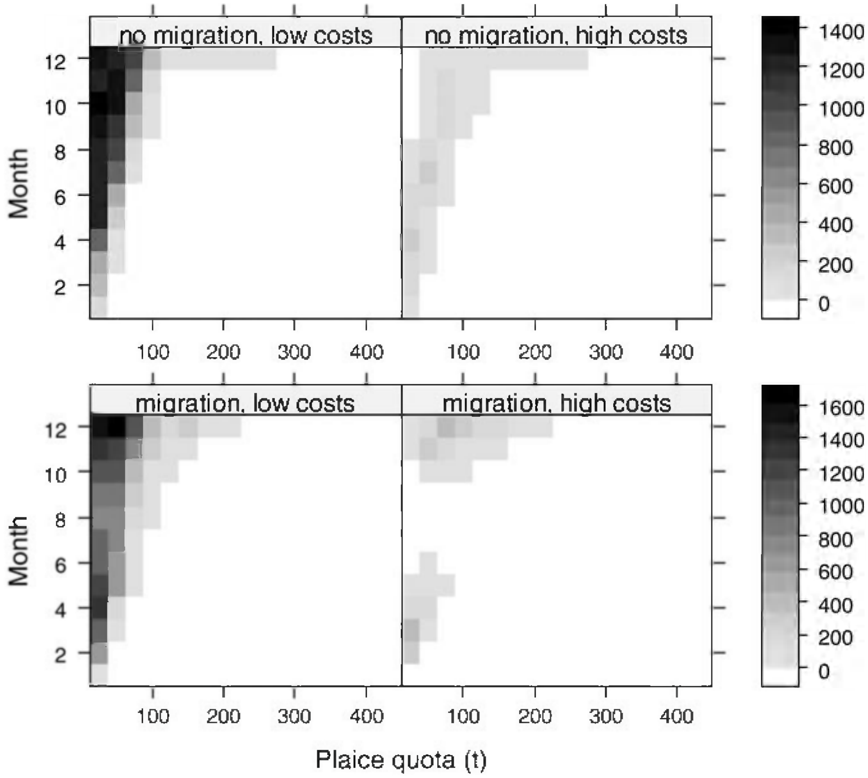

Figure 5. Modelled seasonal pattern in total over-quota discarding (t) of marketable plaice for different levels of plaice quota assuming constant spatial distribution of fish and low fishing costs (top left panel) and high fishing costs (top right panel), or assuming seasonally varying distribution of fish and low fishing costs (bottom left panel) and high fishing costs (bottom right panel).

peaks there. If the plaice quota decreases, total effort in the northern area decreases and effort allocation patterns increasingly resemble those found in the absence of migration, with fishing effort concentrated in the south.

The spatio-temporal distribution of fishing effort reflects the choice of individual vessels to visit different areas throughout the year (Figure 3). With high quotas of plaice, monthly totals of fishing effort increase in late summer, when vessels tend to visit the northern area. The duration of that period depends on the costs of fishing effort. If costs are low, the northern area is visited for 3 months, but if costs are high, the period lasts just 1 month. At the beginning and the end of the year, fishing effort is low because the southern area is more profitable, requiring less travel time. With decreasing levels of plaice quota, fishing effort shifts to the southern area, similar to the models in which no migration was assumed. However, a decrease in fishing effort associated with high costs of fishing takes place at the end of summer, after which effort increases again in winter. This temporal pattern in effort allocation is caused by the seasonal density of plaice in the southern area.

In general terms, the effect of plaice quota on catch and effort in the presence of plaice migration are similar to the situation without plaice migration. Decreasing plaice quotas leads to a decrease in plaice catches and an increase in sole catches, caused by the changes in catchability attributable to the redistribution of effort (Figure 4). At very low plaice quotas, catches of the two species may decline or level off, depending on the costs of fishing. However, in contrast to the situation with no migration, the average catch rates for plaice when plaice quotas are high depend on the costs of fishing: if costs are low, more fishing effort is allocated in the northern area, with its higher catch rate of plaice.

In the presence of migration, the temporal distribution of total discards of marketable plaice with very low quotas of plaice is bimodal. The two periods with high discarding concur with the high catches of plaice in the southern area (Figure 5). At the level of the individual fisher, the optimal strategy again is to retain all marketable plaice until the vessel's plaice quota is reached.

Observations

Data from the mandatory logbooks provide insight on the centre of gravity of fishing effort of the entire fleet between 1990 and 2007. The mean latitude varies seasonally and ranges between 52.5 and 54.5° (Figure 6). The simple linear model disentangling the seasonal and long-term trends in all 216 observations explains some 71% of the variance, using 13 degrees of freedom. Each term in the model has a p-value of <0.01. The seasonal pattern estimated by the model indicates that the fleet starts fishing in the southern areas in the first few months of the year and that as the year progresses, the spatial distribution of fishing effort shifts north, then is followed by a southward movement towards the end of the year. Since 1990, fishing effort has shifted gradually south by more than a half degree of latitude, a trend that was especially strong in the 1990s.

In the voluntary electronic logbook data, 8 of the 20 fishers reported discarding of marketable plaice or sole in 21 trips (sole 7; plaice 14) out of the total of 222 trips that had comments

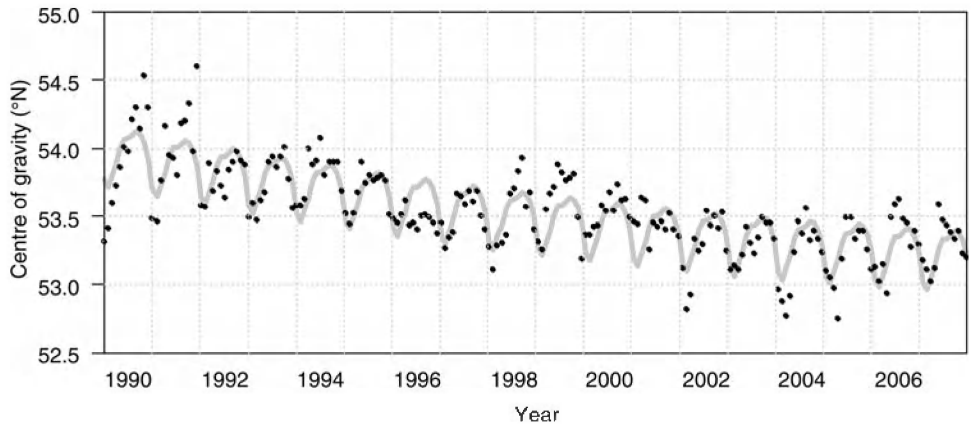

Figure 6. Time-series of the monthly centre of gravity of the Dutch beam-trawl fleet latitudinally. Each dot represents the centre of gravity in a single month, calculated from the mandatory logbook data. The grey line represents monthly predictions of the centre of gravity, using a simple generalized linear model, as described in the text.

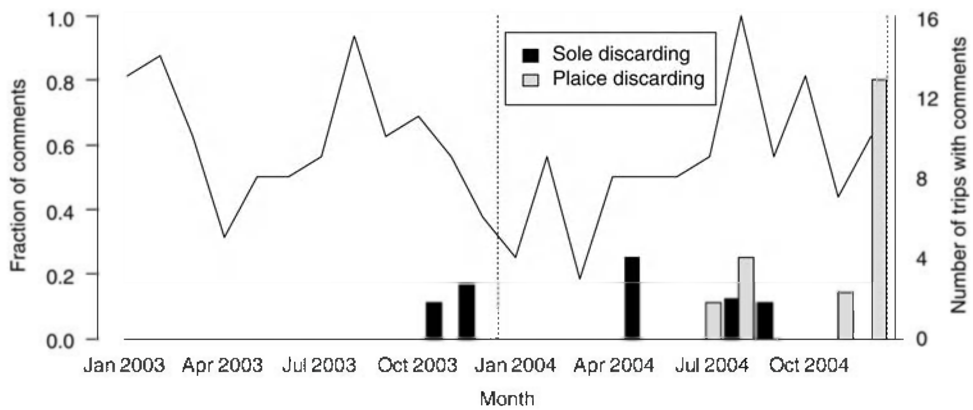

Figure 7. Time-series of the number fishing trips indicating discarding of marketable plaice and sole. Each bar represents the fraction of comments that mention discarding in the voluntary logbooks in a given month (left *y*-axis). The drawn line indicates the total number of trips for which a comment exists per month (right *y*-axis), and the vertical dotted lines the start of the year.

added to haul data (Figure 7). The probability of a comment in the logbook mentioning discarding of marketable fish increased towards the end of the year, indicating that marketable fish are discarded mainly then. In December 2004, 80% of the comments indicated discarding of marketable plaice in the trips reported ($n = 10$). In all five cases where the reason for discarding marketable plaice was reported, fishers stated that they discarded because of their lack of sufficiently large quota. In two cases, along with the lack of sufficiently large quota, low fish price was given as a reason. For sole, no reason for discarding marketable fish was given.

Discussion

This study has characterized spatio-temporal effort allocation and discarding in a multispecies fishery managed by single-species individual quotas using a dynamic-state variable model. The results of the model clearly show that individual quotas on one species (plaice) influence effort allocation and discarding by individual fishers and as a consequence may affect the catchability of another species (sole). Constraining the quota of one species will result in a shift of fishing effort away from areas with high catches of that species towards areas with profitable catches of other species that are not constrained by quota. Hence, in a multispecies fishery, increasing the quota restrictions for one species may reduce the catchability for that species and increase the catchability for other target species. In the North Sea beam-trawl fishery, decreasing individual quotas for plaice result in reallocation of fishing effort to the southern areas, where plaice catches are smaller and sole catches bigger. The model predictions of seasonality in spatial effort allocation, and the southward shift of effort allocation in the 1990s when the individual plaice quotas became increasingly constraining (Quirijns *et al.*, 2008), are confirmed by observations of the fleet. The findings are consistent with the notion that targeting by the beam-trawl fleet between 1990 and 2005 varied in relation to quota restrictions (Quirijns *et al.*, 2008).

Also, constraining quotas for one species may result in more discarding of marketable fish. In the situation explored here, the fleet was to some extent capable of reducing over-quota discarding by reallocating fishing effort and increasingly targeting the species for which the quota limits were not restrictive. Also, over-quota discarding depends on the net revenue that can be generated by fishing while only landing those species for which the quotas have not been depleted. In general, over-quota discarding will occur towards the end of the year, as our model results indicate.

However, at very low levels of quota, many fishers will have exhausted their quotas early in the year. In the specific case studied here, the discarding is in the southern area, used by the fishery because of the high catches of "alternative species". The model results are in line with the observations of discarding of marketable plaice in the Dutch beam-trawl fishery in 2004, when discarding of marketable plaice in the second half of the year peaked in December. This discarding practice coincided with the period when plaice quotas were highly restrictive (Quirijns *et al.*, 2008). The comments made by fishers revealed that their reasons for discarding were mainly insufficient quota and perhaps low fish price.

It should be noted that the discards modelled in this study are part of the marketable catch. This form of discarding differs from minimum landing size (MLS) discarding that consists of the non-marketable part of the catch. MLS discarding may in itself already constitute a large part of the catch (Rijnsdorp and Millner, 1996; van Beek, 1998). The marketable fish in the model are represented as one homogeneous group and are discarded as such. In the real fishery, the marketable catch consists of several classes that differ in value, and the fish with the lowest value will probably be discarded first. This type of discarding, based on market value, is known as highgrading (Anderson, 1994; Gillis *et al.*, 1995; Kingsley, 2002). In the fishery on which this study is based, there can be such highgrading, because differences in price between market categories may be as much as 100% (Taal *et al.*, 2005). In autumn, the fish of low value are the smallest size classes, whereas in winter and early spring such fish may be the largest fish, including spent females of low condition and watery flesh. Such differentiation in classes of different value may influence the temporal distribution of discarding. Low-value fish at the beginning of the year will be discarded to save quota for high-value fish at the end of the year, so giving results different from those obtained by our model, which assumes a single value for all marketable fish. In the electronic logbooks, fishers reported discarding specific size classes of marketable fish, consistent with the notion of highgrading. Moreover, fishers reporting highgrading of marketable plaice continued to land plaice in subsequent weeks, implying that they optimized according to price differences within the species. Our model was unable to evaluate highgrading within a species because each species was modelled as a single homogeneous group.

The effort reallocation found under decreasing plaice quotas depends on the parameters defining the difference in profitability between the various areas. For example, if the difference in prices between species was larger, fishing in the southern region would be more profitable when plaice harvest is unconstrained. In that case, fishing effort would be allocated in the southern area independent of quota size. The maximum plaice catches would be lower, but the temporal discarding pattern would be similar to that found in this study. If the spatial distribution of species were to differ, discarding of plaice might be greater because the reallocation of fishing effort to areas with lower catches of plaice, higher catches of sole, and lower fishing effort requirements depends on the spatial distribution used in the model.

The assumption of maximizing economic performance has been evaluated before. The response of fishing vessels to catch rate has been shown in, for example, British Columbia salmon seining (Hilborn and Ledbetter, 1979) and shrimp trawling (Eales and Wilen, 1986). The response has been used to formulate models predicting the distribution of fishing vessels (Gillis *et al.*, 1993). Our model uses a similar assumption, but takes into account a broader behavioural context by incorporating discarding behaviour and the requirement to respect the rules set by fisheries management. It is clear that restrictive quotas influence the spatial distribution of fishing effort and discarding behaviour. The latter allows fishers to continue fishing in a multispecies fishery if one of the quotas is exhausted, depending on the costs of fishing effort.

Our model assumes that fishers have perfect information about the distribution of catch rates in many areas. The knowledge of individual fishers on the distribution patterns of target species depends on the predictability of the resource distributions (van Densen, 2001), as well as the level of information sharing within the fleet. The predictive value of observations in the beam-trawl fleet appears to be relatively high (Poos and Rijnsdorp, 2007a), in particular with regard to the seasonal migration of adult fish (de Veen, 1976; Hunter *et al.*, 2003; Bolle *et al.*, 2005) and the recruitment of the incoming year class (Beverton and Holt, 1957). To increase knowledge of the spatial distribution of catch rates, fishers may exchange information. The role of information exchange in acquiring knowledge of the distribution of the target species has been discussed by Curtis and McConnell (2004).

The effects of the size of individual quotas on catchability of all target species and over-quota discarding have serious implications for fisheries management. First, increased catchability for species not restricted by quotas may be the undesired result of setting individual quotas in a multispecies fishery. Second, if a part of the catch is not landed, a bias may be introduced in the analytical stock assessments supporting the management of many fisheries (Rijnsdorp *et al.*, 2007). Because the discarding of marketable fish is concentrated at the end of the year and is mainly associated with vessels with relatively small individual quotas, it is difficult to estimate the level of this form of discarding from the current North Sea discard sampling programmes that combine low sampling levels ($<1\%$ of the trips) with regularly spaced samples throughout the year (van Keeken *et al.*, 2004; STECF, 2008).

The high fines for exceeding the quota resulted in vessels remaining in port when quotas were low because over-quota fish did not contribute to their economic revenue. However, in reality fishers may assess the potential benefit of the economic return of over-quota landings against the cost of running a risk of being penalized for misreporting. Non-compliance could lead to a higher over-quota catch of plaice. Our results assume high fines in combination with strong enforcement. High fines can also be interpreted as fisher desire to respect a quota. Additional analysis could give insight into the relation between the level of the fines and the compliance with the quota. If over-quota discarding is to be reduced, high fines on over-quota discarding could be implemented, as in a discard ban. However, such a measure is considerably more difficult to enforce than individual landing quotas. Assuming that strong enforcement is possible, the effects of a discard ban can be analysed in the present model by removing the discard options to the vessel.

The individual optimization models presented here ignore the possibility that the behaviour of other members in the fisher population affect the choices of the focal individual (Clark and Mangel, 2000). This has two important implications for the results presented in this study. First, the model ignores exploitation or interference competition affecting the catch rates as a result of high vessel density. Such competition may decrease the catch rate as a function of the number of competing vessels in an area

(Fretwell and Lucas, 1970; van der Meer and Ens, 1997). Interference competition may play a role in fisheries worldwide (Gillis, 2003), including the Dutch flatfish fishery (Rijnsdorp *et al.*, 2000; Poos and Rijnsdorp, 2007b).

Second, the model does not allow for transferability of quotas between fishers: quotas cannot be leased from one vessel to another during a year, although this is one of the key points of ITQ systems. Conditions may exist where the transfer of a quota is beneficial for two individuals: given the stochastic nature of catches, one fisher may have reached his quota before the end of the year, because of a sequence of good catches, whereas another may realize he will not reach his quota, because of a sequence of poor catches. A transfer in ITQ will increase the net revenue of both vessels. If all vessels are equal, this effect could be especially strong at quota levels close to maximum catch levels. At a higher quota, no vessel will be restricted by it, and there will be no incentive to transfer quota. At a lower quota, all vessels will be restricted by its level, and no vessel will have excess quota to transfer. Such a hypothesis needs careful testing using robust models. The extension of dynamic-state variable models with frequency dependence has been described (Clark and Mangel, 2000), and the method should be considered in future to analyse the effects of transferability of quota on discarding behaviour.

The discarding of marketable fish under conditions imposed by management, mitigated by the spatio-temporal distribution of resources, has important implications for fisheries management. Over-quota discarding will disrupt the link between catches and landings in mixed fisheries and may corrupt the basis of scientific advice and increase the risk of stock collapse (Rijnsdorp *et al.*, 2007). This can be tested by using the model described here in studies evaluating fisheries management, employing the framework developed in the International Whaling Commission (Kirkwood, 1997; McAllister *et al.*, 1999). In such a framework, the population dynamics of fish stocks and the dynamics of fishing fleets are modelled (Butterworth and Punt, 1999; Punt *et al.*, 2002). The biological detail is often very high (Kell and Bromley, 2004), but the response of the fleet to the constraints applied has generally been captured in simplistic assumptions, such as fixed catchabilities for the species being modelled, with all excess catch being discarded (Pastoors *et al.*, 2007). The model presented here allows calculation of the economic optimum strategy for fishing fleets under input or output constraints. Hence, it has the potential to add detailed fleet response to management rules, predicting effort, catch, and discard levels in evaluation frameworks.

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