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Quota allocation in mixed fisheries: a bioeconomic modelling approach applied to the Channel flatfish fisheries

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Abstract :

A simulation modelling approach is used to assess the respective performances of different regimes of quota allocation (fixed or transferable), quota ownership (owned or not by fishers), and taxation for catching fish above quota. The simulations account for a variety of fleet behaviours (ranging from fixed by tradition to dynamic economics-driven). The modelling framework is applied to the Channel flatfish mixed fisheries. Transferable quota allocation regimes would particularly benefit small netters and beam trawlers, which would achieve a profit of €50–150 million without compromising the conservation of eastern Channel sole, but it could impair the sustainability of other stocks. If quota is owned by fishers, the least fishing-efficient fleet stops fishing, but makes substantial profit from leasing quotas to beam trawlers and to small and large netters, which remain actively fishing. The highest economic return for quota owners (€200–300 million) is achieved when effort allocation is fixed by tradition. The profit achieved by small netters is greatest when fleets are almost entirely economics-driven. Increasing overquota landing taxes generally leads to conservation benefits for all stocks, but at the expense of lower profitability for the fishery overall.

Keywords : Channel flatfish mixed fisheries ; fisheries management ; fleet dynamics ; individual quotas ; overquota landing tax ; plaice (Pleuronectes platessa) ; sole (Solea solea)

1. Introduction

Fisheries managers worldwide employ a range of measures to achieve their objectives, trying to control either the biological or the economic status of the fishery (Thébaud et al., 2007). The aim of biological measures is to ensure a high level of productivity of the resource by limiting fishing mortality to a level consistent with the reproductive capacity of the harvested stocks. Such measures include catch limits (e.g. total allowable catches, TACs), fishing effort restrictions, and a suite of technical measures.

The aim of economics-orientated measures is to allocate predetermined levels of overall fishing possibilities between fishing firms in order to avoid the race for fish phenomenon and the negative consequences for the economic efficiency of fisheries. The measures involve either implementing the standards set by governance bodies (e.g. catch quotas, limits on days at sea, technical measures), or the introduction of economic incentives (including taxation schemes or tradable right systems). Individual quotas (IQs), particularly individual transferable quotas (ITQs), have attracted considerable attention from both the scientific community and fisheries management agencies since the 1970s (Arnason, 1990, 2007; Annala et al., 1991; Grafton, 1996). They are widely recognized to prevent the race for fish and, when transferable, are believed to increase the economic efficiency of fishing activities (Grafton et al., 2000; Hersoug et al., 2000; Costello et al., 2008).

IQs represent a prevalent form of fisheries management in countries such as Australia, Canada, Chile, Iceland, The Netherlands, and New Zealand. In the European Union (EU), the common fisheries management framework builds mainly on biological measures and only to a limited extent on access-regulation measures. At the level of EU Member States, quota allocation procedures are usually not explicit, except in the Netherlands and Denmark, where ITQs are implemented formally (Marchal et al., 2009b). There are ongoing discussions around the common implementation of IQs to regulate the access of fisheries resources in EU waters, and about the type of catch-quota balancing mechanisms that could be adopted (EC, 2007, 2009). In support of the political debate, scientific reviews and investigations have been encouraged to evaluate whether and to what extent EU fisheries would benefit from a generalized rights-based management regime.

The scientific literature dealing with the modelling and subsequent evaluation of IQ-based management regimes has grown quickly in recent decades. Most of the literature, however, focuses on single-species fisheries concepts (Arnason, 1990; Boyce, 2004) or case studies (Armstrong and Sumaila, 1991; Kulmala et al., 2007; Chavez et al., 2008; Hamon et al., 2009). Some studies have investigated the static optimal allocation of quotas in mixed-species fisheries subject to an ITQ regime (Squires and Kirkley, 1996; Arnason, 1998). The determination of quota prices is an important step in capturing the process of quota allocation, and this has been investigated using empirical approaches (Batstone and Sharp, 2003) or conceptual models (Arnason, 1990; Holland and Herrera, 2006). A comprehensive dynamic bioeconomic model has been developed by Little et al. (2009) to model the effect of various management options on the ITQ-regulated Australian coral reef mixed fishery. This spatially and monthly dynamic model integrates all components of the fishery system (management, economics, fleet behaviour, quota market, and fish ecology).

In this paper, we use a similar model to evaluate the respective merits of management strategies based on catch shares, in the case of a fishery that has never been regulated by a formal IQ system: the (English) Channel flatfish fishery. At the time of writing, it is not clear which type of quota allocation regime will be implemented in EU waters (EC, 2007). Some of the most debated issues are the extent to which quota would be individualized and made transferable, and the question of who (e.g. the fishers, producer organizations, government bodies, the general public) would be able to own the quota. Another issue at stake is the type of mechanism that should be adopted to ensure a reasonable match between catches and quotas in mixed fisheries (Sanchirico et al., 2006).

We here considered three alternative quota allocation and ownership regimes. In the first and the second scenarios, quota shares are allocated to the fleets by a quota holding organization (QHO), which could be a public authority (e.g. a state, the Crown), or a private organization (e.g. a producer organization). With the first scenario, quota shares are allotted to Channel fishing fleets with a time-invariant allocation key, so transfers are not allowed. With the second scenario, transfers are simulated by allowing the QHO to adapt the number of quota shares they lease to the different fleets. With the third scenario, quota shares are owned by the fishing fleets, and are transferable. In both the second and third quota allocation scenarios, quota transfers are determined by a fleet's economic performance.

We also investigated the impact of two key drivers on the performance of these three quota allocation regimes, (i) fleet dynamics under various behavioural assumptions, ranging from fixed to economically driven fishing (Hilborn and Ledbetter, 1979; Hilborn, 1985; Marchal *et al*., 2009a) and, (ii) an economic incentive aiming at discouraging overquota landings.

2. Methods

2.1. Modelling framework

Our model builds on version 3.1.3 of the ISIS–Fish simulation platform (http://www.ifremer.fr/isis-fish). The ISIS–Fish model consists of spatially explicit population dynamics and exploitation submodels that describe how a selection of fishing fleets operate in a discrete number of métiers, and harvest a mixture of commercial species. The equations of the base model are fully detailed in Mahévas and Pelletier (2004), Pelletier and Mahévas (2005), and Pelletier *et al.* (2009), and summarized in the Supplementary material to this paper.

In addition to the existing base model, fleet behaviour and management submodels have been developed, using Java Script, to capture quota price-setting, quota allocation, fleet behaviour, and catch-quota balancing. These processes have been implemented at the scale of the fishing fleet, so it is assumed that quota is allocated to fishing fleets and that all vessels belonging to the same fleet have the same average behaviour. The model runs at a monthly time-step starting in 2009, and is projected to 2028. An initialization period of one year (2009) is needed to calculate the fleet allocation of the catch quota.

2.2. Catch-quota matching mechanism

In the model we consider that discarding is prohibited, and cannot be used to match landings to quota for any species. The catch-quota matching mechanism used consists of imposing a tax on every kilogramme of fish landed above quota, and is referred to as an overquota landing tax (OLT, expressed in € kg^{-1}). Note that an OLT is currently implemented in New Zealand (Holland and Herrera, 2006). The total charge paid by fleets for landing fish above quota is the product of overquota landings and the OLT, and is referred to as the overquota landing payment (OLP, expressed in €).

2.3. Quota-lease price-setting

Quota price may be calculated based on the short-term average marginal profit among fishing units (Guyader and Thébaud, 2001; Little *et al.*, 2009). The marginal profit per fishing unit represents the price each fishing unit is prepared to pay for the quota of a species. The difference between the marginal profit and the quota-lease price represents the net marginal benefit of harvesting an additional unit of fish; if this is positive/negative for some fleets, they will be interested in leasing in/out quota. Assuming perfect market adjustment, net demand/supply for quota will clear when the quota-lease price is equal to the marginal profit (Guyader and Thébaud, 2001).

Although a number of approaches have been developed to model quota price for one or two species at a time (Arnason, 1990; Holland and Herrera, 2006), there have been few attempts to model simultaneously the quota price of several species in a generic way. In one such approach to calculating quota-lease price, Little *et al.* (2009) derived a marginal profit per vessel for species *s* as the product between (i) the anticipated proportion of species *s*, and (ii) the difference between the price of species *s* and the marginal running cost per unit of all fish caught.

Here we used the same approach but with the basic fishing unit being the fishing fleet (i.e. a set of fishing vessels with similar characteristics). It was also assumed that the minimum quota price is 5% of landing price. This arbitrary lower bound reflects the necessity to offset cost-recovery levies and other transaction costs (Holland and Herrera, 2006). Finally, it was assumed that a maximum quota price should be set against the OLT. This upper bound reflects the fact that fishing fleets would rather pay an OLP than rent a quota if the quota price exceeded the OLT (Holland and Herrera, 2006).

The anticipated marginal profit ($\hat{\mu}_{s,y,k,f}$) of fleet *f* harvesting species *s* in year *y*, month *k* is here defined as the difference between the landing price (*p*) of species *s* (assumed to be constant) and of the anticipated costs of landing 1 kg of fish ($\hat{\chi}_{y,k,f}$), scaled by the anticipated proportion ($\hat{\gamma}_{s,y,k,f}$) of species *s* in the catch. If $Y_{s,y,k,f}$ represents the catch of species *s* in year *y* and month *k* by fleet *f*, $E_{y,k,f}$ the nominal fishing effort (in h fishing), and c_f the average fleet-specific harvesting costs (in € h^{-1}), the anticipated short-term marginal profit of fishing is formulated as

$$\begin{cases} \hat{\mu}_{s,y,k,f} = 0.05\, p_s \text{, if } \hat{\mu}_{s,y,k,f} \leq 0.05\, p_s \\ \hat{\mu}_{s,y,k,f} = \hat{\gamma}_{s,y,k,f}\left(p_s - \hat{\chi}_{y,k,f}\right) \text{, if } 0.05\, p_s < \hat{\mu}_{s,y,k,f} < \mathrm{OLT}_s \\ \hat{\mu}_{s,y,k,f} = \mathrm{OLT}_s \text{, if } \hat{\mu}_{s,y,k,f} \geq \mathrm{OLT}_s \end{cases} . \tag{1}$$

We assumed that $\hat{\gamma}_{s,y,k,f}$ could be approximated as the actual proportion in landings of species *s* averaged over the previous 12 months:

$$\hat{\gamma}_{s,y,k,f} = \frac{Y_{s,y-1,k,f} + \ldots + Y_{s,y,k-1,f}}{\sum_s \left(Y_{s,y-1,k,f} + \ldots + Y_{s,y,k-1,f,}\right)}, \tag{2}$$

and $\hat{\chi}_{y,k,f}$ as the anticipated marginal costs averaged over the previous 12 months,

$$\hat{\chi}_{y,k,f}=\frac{c_f\left(E_{y-1,k,f}+\ldots+E_{y,k-1,f}\right)}{\sum_{s}\left(Y_{s,y-1,k,f}+\ldots+Y_{s,y,k-1,f}\right)}. \tag{3}$$

The overall quota price (q) of species s was then calculated as the anticipated marginal profit averaged across all N_f fleets (Little *et al.*, 2009):

$$q_{s,y,k}=\bar{\hat{\mu}}_{s,y,k,f}=\frac{1}{N_f}\sum_{f}\hat{\mu}_{s,y,k,f}. \tag{4}$$

2.4. Quota allocation

Three scenarios were considered for allocating TAC to the different fishing fleets, aimed at reflecting some of the options advocated in EC (2007). The three scenarios differ in terms of the procedures chosen to simulate quota transfers and quota ownership.

2.4.1. Fixed quota allocation scenario (QA1)

With this first scenario (QA1), all quota shares are owned by a QHO that leases them to the fleets. To obtain quota, the fleets need to pay a rent to this QHO, or pay an OLP if their quota is exceeded. The proportion of the TAC allocated to each fleet is calculated only once at the start of 2010, on the basis of the aggregate catches recorded in the initial year 2009, and is not modified thereafter. Quota is then allocated to each fleet and stock at the start of each subsequent fishing year. This scenario represents a non-transferable IQ system, with taxation of resource use. Under QA1, the quantity of IQ available to fleet f in year y, after the initial year 2009, and in month k is formulated as

$$\mathrm{IQ}^{\mathrm{QA1}}_{s,y\geq 2010,k,f}=\left[\frac{\sum_{t=1}^{12}Y_{s,y=2009,t,f}}{\sum_{f}\sum_{t=1}^{12}Y_{s,y=2009,t,f}}\right]\mathrm{TAC}_{s,y}-\sum_{t=1}^{k-1}Y_{s,y,t,f}. \tag{5}$$

In the course of the year, the amount of quota available for any fleet to catch will decrease as a result of accumulating catches.

2.4.2. Transferable quota organized by QHO (QA2)

In this second scenario, all TAC shares are owned by a QHO, which leases them to the fleets in proportion to their economic performance. As a result, the quota allocated to each fleet can vary from year to year. Quotas are initially allocated at the start of 2010 in proportion to the aggregate catches recorded in 2009. In subsequent years, quota is allocated such that the more a fleet can extract profit from a quota unit, the more it will be prepared to pay a high price to rent a quota from the QHO, and the more the quota will be harvested in an economically efficient manner (i.e. in a profit-maximizing fashion). A mechanism that can ensure such an allocation in practice could be an annual auction of catch shares by the QHO. As a consequence, the fleets do not extract the economic benefits of trading quotas, which are taken by the QHO.

We make the additional assumption that quota exchanges are instantaneous at the start of a year, and not continuous throughout that year, an assumption supported by the fact that the fishing strategies of EU fleets are commonly determined on an annual basis (ICES, 2003;

EC, 2005). The quota rent, however, is paid by the fleets to the QHO on a monthly basis, building on quota prices derived from Equations (1)–(4). The quota available throughout the year under scenario QA2 is expected to decrease as a result of accumulating catches:

$$\begin{cases} \mathrm{IQ}^{\mathrm{QA2}}_{s,y=2010,k,f} = \left[\dfrac{\sum_{t=1}^{12} Y_{s,y=2009,t,f}}{\sum_{f}\sum_{t=1}^{12} Y_{s,y=2009,t,f}}\right]\mathrm{TAC}_{s,y} - \sum_{t=1}^{k-1} Y_{s,y=2010,t,f} \\ \\ \mathrm{IQ}^{\mathrm{QA2}}_{s,y>2010,k,f} = \left[\dfrac{\max\left(\hat{\Pi}^{\mathrm{QA2}}_{s,y,f},0\right)}{\sum_{f}\max\left(\hat{\Pi}^{\mathrm{QA2}}_{s,y,f},0\right)}\right]\mathrm{TAC}_{s,y} - \sum_{t=1}^{k-1} Y_{s,y,t,f} \end{cases}, \qquad (6)$$

where the first equation allocates quota in 2010 based on the aggregate catches in 2009, and the second operates once the first year of profits have been determined based on the first year of quota allocation in 2010. The species-specific anticipated profit $\hat{\Pi}^{\mathrm{QA2}}_{s,y,f}$ in these equations is formulated as

$$\hat{\Pi}^{\mathrm{QA2}}_{s,y,f} = \hat{\gamma}_{s,y,k=1,f}\sum_{t=1}^{12}\left[\left(\sum_{s}\left(\left(p_s - \rho_{s,y-1,t,f}\right)Y_{s,y-1,t,f}\right)\right) - c_f\, E_{y-1,t,f}\right], \qquad (7)$$

where $\rho_{s,y-1,t,f} = q_{s,y-1,t}\left(\text{if } \mathrm{IQ}^{\mathrm{QA2}}_{s,y-1,t,f} \geq 0\right)$ or $\mathrm{OLT}_s\left(\text{if } \mathrm{IQ}^{\mathrm{QA2}}_{s,y-1,t,f} < 0\right)$.

Under this scenario, species quota for fleet *f* at the beginning of the year is proportional to the anticipated annual profit realized by fleet *f* in relation to that species ($\hat{\Pi}^{\mathrm{QA2}}_{s,y,f}$). We assume here that $\hat{\Pi}^{\mathrm{QA2}}_{s,y,f}$ depends on the revenue accumulated by fleet *f* during the previous year, on the average annual harvesting costs, but also on the anticipated species-specific catch composition of fleet *f* ($\hat{\gamma}_{s,y,k,f}$), as defined in Equation (2). Also, $\hat{\Pi}^{\mathrm{QA2}}_{s,y,f}$ is constrained so that the anticipated species-specific profits of fleets with negative value are set to zero, which results in no quota being allocated to these fleets at the beginning of the year.

2.4.3. Transferable quota allocation organized by the fishing fleets (QA3)

With the third scenario (QA3), all fleets own the proportion of the TAC they have been allocated at the beginning of 2010, based on their respective 2009 aggregate catches (the same allocation procedure as for scenarios QA1 and QA2). In subsequent years, quota leases between fleets are made on the basis of the profitability of their fishing activity. Therefore, at the start of each year, it is assumed that each fleet trades quota in such a way that they obtain a quantity of quota proportional to the annual species-specific profit they anticipate from their fishing activity ($\hat{\Pi}^{\mathrm{QA3}}_{s,y,f}$). Similar to scenario QA2, it is assumed here that the anticipated profit, i.e. $\hat{\Pi}^{\mathrm{QA3}}_{s,y,f}$, depends on the revenue accumulated by fleet *f* during the previous year, on the average annual harvesting costs, and on $\hat{\gamma}_{s,y,k,f}$, and that negative values of $\hat{\Pi}^{\mathrm{QA3}}_{s,y,f}$ are set to zero. Quota transactions are conducted only at the start of the year. Should their quota provision be exceeded during the year, it is assumed that the fleets pay an OLP. The quota available at month *t* under scenario QA3 ($\mathrm{IQ}^{\mathrm{QA3}}_{s,y,k,f}$) is defined as in Equation (6), but substituting $\hat{\Pi}^{\mathrm{QA2}}_{s,y,f}$ with $\hat{\Pi}^{\mathrm{QA3}}_{s,y,f}$. The species-specific anticipated profit $\hat{\Pi}^{\mathrm{QA3}}_{s,y,f}$ is defined as

$$\hat{\Pi}^{\mathrm{QA3}}_{s,y,f} = \hat{\gamma}_{s,y,k=1,f} \sum_{t=1}^{12} \left[\left(\sum_{s} \left(\left(p_s - \rho_{s,y-1,t,f} \right) Y_{s,y-1,t,f} \right) \right) - c_f \; E_{y-1,t,f} \right], \qquad (8)$$

where $\rho_{s,y-1,t,f} = 0 \left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y-1,t,f} \geq 0 \right) \text{ or } \mathrm{OLT}_s \left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y-1,t,f} < 0 \right)$.

Note that unlike under the QA2 scenario [Equation (7)], quota price (*q*) does not factor into Equation (8). This is because the anticipated profit functions used to determine quota allocations require only the returns generated from fishing, not from trading quota. Under the QA2 scenario, a fleet needs to pay for all of the quota it obtains, whereas under the QA3 scenario, where the fleet owns quota, only a portion of any additional purchased allocation is a cost, and is offset by a return in other fleets that sell their allocation. Therefore, the TAC allocation in the QA3 scenario is based only on fishing performance, and does not include quota-trading payments. This procedure allows the most efficient fleets that do not own enough quota shares to obtain additional quota from other fleets that make more profit from leasing quota than from fishing.

2.5. Fleet behaviour

Both economic and non-economic factors are key determinants of fisher decision-making (Holland and Sutinen, 1999; Hutton *et al.*, 2004; Vermard *et al.*, 2008; Marchal *et al.*, 2009b). In the model here, each fleet may operate different métiers, the choice of métier being determined by a combination of tradition and economic incentives. For any fleet *f*, the total fishing effort per month (number of days fishing summed over all métiers operated by *f* during one month) is modelled through a simple procedure. Hence, the total effort per fleet is assumed constant and set to its 2009 value, as long as at least one métier operated by that fleet is expected to provide a positive profit. However, if all the métiers operated by *f* are expected to lead to negative profit, then fishing ceases in the following month and the fishing effort of that fleet is set to zero.

It is assumed that the proportion of the effort allocated to métier *m* at time *t*, initially set to the 2009 value, depends dynamically on two quantities. The first is the ratio between the monthly fishing profit anticipated from métier *m* ($\hat{\pi}_{y,k,f,m}$) and the monthly fishing profit anticipated from all métiers. Quantity $\hat{\pi}_{y,k,f,m}$ is set to the actual monthly profit realized in the previous year. The second quantity is a fleet's traditional effort allocation, which is here derived from the actual values observed during the same month and the previous fishing year. The relative weights given to the anticipated profit and traditions are defined by a parameter α that we varied. The proportion of nominal effort (*E*) of fleet *f* allocated to métier *m* may then be formulated as

$$E_{y\geq 2010,k,f,m}=\begin{cases}\alpha\left[\dfrac{\max\left(\hat{\pi}_{y,k,f,m},0\right)}{\sum_{m}\max\left(\hat{\pi}_{y,k,f,m},0\right)}\right]+(1-\alpha)\left[\dfrac{E_{y-1,k,f,m}}{\sum_{m}E_{y-1,k,f,m}}\right]\text{ if }\sum_{m}\max\left(\hat{\pi}_{y,k,f,m},0\right)>0\\[2ex] 0\;\forall m\text{ if }\sum_{m}\max\left(\hat{\pi}_{y,k,f,m},0\right)=0\end{cases},\qquad(9)$$

where $E_{y,k,f}=\sum_{m}E_{y,k,f,m}$. The α parameter quantifies the relative weights of traditions and of anticipated economic return in determining effort allocation, similar to Soulié and Thébaud (2006). Different values of α ranging between 0 and 1 were examined. For example, when $\alpha = 1$, fishing behaviour is driven entirely by anticipated profit. When $\alpha = 0$, fishing effort allocation is completely unresponsive to changes in relative profit across métiers.

The second condition of Equation (9) reflects the fact that the total fishing effort of fleet *f* is set to zero when the anticipated profit of all métiers operated by that fleet is negative. The anticipated monthly fishing profit per métier $\hat{\pi}_{y,k,f,m}$ is defined as

$$\hat{\pi}_{y,k,f,m}=\left(\sum_{s}\left(p_{s}-\rho_{s,y,k,f}\right)Y_{s,y-1,k,f,m}\right)-c_{f}\,E_{y-1,k,f,m}\;,\qquad(10)$$

where $Y_{s,y,k,f}=\sum_{m}Y_{s,y,k,f,m}$.

Under scenarios QA1 and QA2, $\rho_{s,y,k,f}=q_{s,y,k}\left(\text{if } \mathrm{IQ}_{s,y,k,f}\geq 0\right)$ or $\mathrm{OLT}_{s}\left(\text{if } \mathrm{IQ}_{s,y,k,f}<0\right)$, where $\mathrm{IQ}_{s,y,k,f}$ is respectively $\mathrm{IQ}^{\mathrm{QA1}}_{s,y,k,f}$ and $\mathrm{IQ}^{\mathrm{QA2}}_{s,y,k,f}$. Under scenario QA3, $\rho_{s,y,k,f}=0\left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y,k,f}\geq 0\right)$ or $\mathrm{OLT}_{s}\left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y,k,f}<0\right)$.

2.6. Economic performance

The economic performance of the fishery system was evaluated by investigating the annual profit actually realized by the fleets [Equations (11a) and (11b)], the annual return realized by the QHO for scenarios QA1 and QA2 [Equation (12)], and the OLP [Equation (13)]. With QA1 and QA2, the actual profit achieved by fleet *f* in fishing year *y* builds on the total costs and earnings resulting from fishing activities cumulated over that year, and is written as

$$P_{y,f}=\sum_{t=1}^{12}\left(\left(\sum_{s}\left(\left(p_{s}-\rho_{s,y,t,f}\right)Y_{s,y,t,f}\right)\right)-c_{f}\,E_{y,t,f}\right),\qquad(11a)$$

where $\rho_{s,y,t,f}=q_{s,y,t}\left(\text{if } \mathrm{IQ}_{s,y,t,f}\geq 0\right)$ or $\mathrm{OLT}_{s}\left(\text{if } \mathrm{IQ}_{s,y,t,f}<0\right)$, where $\mathrm{IQ}_{s,y,t,f}$ is calculated using Equations (5) or (6), respectively.

For scenario QA3, the actual profit function in year *y* includes the outcomes of fishing activities (as for QA1 and QA2), as well as the result of quota transactions between the different fleets at the start of the year. As the proportion of the TAC owned by the different fleets is time-invariant, the gains and losses resulting from quota transactions are always indexed to the quota share initially allocated in 2010. The actual profit function under scenario QA3 may then be formulated as

$$P^{\mathrm{QA3}}_{y,f} = \sum_{s} q_{s,y,k=1}\left(\mathrm{IQ}^{\mathrm{QA3}}_{s,y=2010,k=1,f} - \mathrm{IQ}^{QA3}_{s,y,k=1,f}\right) + \sum_{t=1}^{12}\left(\left(\sum_{s}\left(\left(p_s - \rho_{s,y,t,f}\right)Y_{s,y,t,f}\right)\right) - c_f\, E_{y,t,f}\right), \tag{11b}$$

where $\rho_{s,y,t,f} = 0\left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y,t,f} \geq 0\right)$ or $\mathrm{OLT}_s \left(\text{if } \mathrm{IQ}^{\mathrm{QA3}}_{s,y,t,f} < 0\right)$. Under scenarios QA1 and QA2, the total economic return (*R*) for the QHO in year *y* may be expressed by

$$R_y = \sum_{t=1}^{12}\sum_{f}\sum_{s} \rho_{s,y,t,f}\, Y_{s,y,t,f}, \text{ where } \rho_{s,y,t,f} = q_{s,y,t}\left(\text{if } \mathrm{IQ}_{s,y,t,f} \geq 0\right) \text{ or } 0 \left(\text{if } \mathrm{IQ}_{s,y,t,f} < 0\right). \tag{12}$$

Finally, for all TAC allocation scenarios, the OLP due by all fleets in year *y* may be expressed by

$$\mathrm{OLP}_y = \sum_{t=1}^{12}\sum_{f}\sum_{s} \rho_{s,y,t,f}\, Y_{s,y,t,f}, \text{ where } \rho_{s,y,t,f} = 0\left(\text{if } \mathrm{IQ}_{s,y,t,f} \geq 0\right) \text{ or } \mathrm{OLT}_s \left(\text{if } \mathrm{IQ}_{s,y,t,f} < 0\right). \tag{13}$$

3. Material

The Channel flatfish fishery consists of several fleets, mainly French gillnetters and English or Belgian beam trawlers, operating in ICES Divisions VIId (eastern Channel) and VIIe (western Channel). The fleets target sole (*Solea solea*), and their main bycatch is plaice (*Pleuronectes platessa*). Other bycatches of the flatfish fishery include turbot (*Psetta maxima*), brill (*Scophtalmus rhombus*), flounder (*Platichtys flesus*), dab (*Limanda limanda*), and cod (*Gadus morhua*).

Sole in the Channel is managed and assessed as two separate units, the main one located in the eastern and the other in the western Channel. Plaice in the Channel is managed as a single stock, but is assessed as two separate stocks, one in the eastern and one in the western Channel. All other stocks are either part of a larger stock of which the Channel component is only a minor component, or poorly monitored.

The Channel flatfish fisheries have been regulated mainly by TACs since 1983. The TAC is allocated to the different EU Member States involved in the fishery based on a fixed allocation key. There is currently no provision in EU legislation for how a national share of the TAC should be distributed to different stakeholders.

3.1. Data

Biological information on sole and plaice was drawn from ICES (2008a, b, c, and d; summarized in Table 1). The other species were bundled into a single “other species” group. It is assumed here that this group’s landings were constant over time (and set to the 2007 value), or null if effort is set to zero. Therefore, the “other species” will affect fleet behaviour, but their population dynamics will not be affected by fishing activities.

Selectivity curves for beam trawlers were of the logistic form suggested by Rijnsdorp *et al.* (1981) for sole and van Beek *et al.* (1983) for plaice (Table 2). For netters, we retained the bi-normal selection curve parametrized by Madsen *et al.* (1999; Table 2). Selection curves were parametrized for a mesh size of 80 mm for beam trawls, and of 100 mm for fixed nets. The selection for the other gears was assumed to be knife-edged for sole and plaice, with 0% retention at age 1 and 100% retention for 2+ age groups. For the other species, the retention rate was assumed to be 100% for all gears.

Five métiers were identified by combining the main gear used (beam trawl, net, or others) with the area visited (eastern or western Channel). The strength by which the different métiers target the different species under consideration is quantified by métier- and species-dependent target factors (Mahévas and Pelletier, 2004). In this investigation, the target factors associated with the Channel sole, plaice, and other species were calculated based on the proportional contribution of each species to the total landings in 2005. For the French and UK fleets, the landings data required to derive the target factors were derived from national logbooks (Anon., 2009). Annual aggregated landings from other nations, and particularly from Belgium, fishing in the Channel were taken from ICES (2008a, b). The different métiers and associated target factors are listed in Table 3.

Four fleets were identified based on the main gear used and vessel size: gillnetters <12 m, gillnetters >12 m, beam trawlers >12 m, and a fleet grouping all other vessels (referred to as the “other vessels” fleet). The initial quarterly allocation of métiers per fleet is given in Table 4. For both eastern and western Channel netters, economic information was available that indicated that operating costs amounted to about 20% of the current fleets’ gross revenue (Anon., 2008). For large beam trawlers, aggregated economic data were available from Anon. (2007), indicating that operating costs amounted to some 50% of the fleets’ gross revenue at current levels of effort. These figures, combined with current gross revenue and fishing effort, were used to derive the average hourly operating costs (€ h^{-1}). In the absence of better information, we assumed that the other fleets behaved like large beam trawlers (ICES, 2008a, b).

Finally, it was assumed that the Channel fishery system could in future be managed by a combination of TAC and OLT that are fixed during the entire simulation period. As the plaice management unit includes two assessment units (eastern and western Channel plaice), we assumed that a fixed TAC share is allotted to the eastern and the western Channel, based on recent landings. On that basis, 80% of the Channel plaice TAC was allotted to the eastern and 20% to the western Channel. For the other species, the TAC was fixed to the status quo landings, which is here assumed to correspond to the total annual biomass. We then obtained five distinct TACs: one for each assessment unit of sole and plaice, and one for the other species. These TACs were defined based on current values (Table 5). The OLT implemented for the different stocks harvested was based on arbitrary values, because this management instrument has not been implemented for the Channel fisheries to date. The OLT was set equal to the first-sale price of fish for each stock (Table 5), but we also explored alternative scenarios where the OLT was respectively set at 50% and 150% of fish price.

4. Results

4.1. Time dynamics

With $\alpha = 0.0$, fishing effort is time-invariant for the métiers netters and beam trawlers. The “others” métiers effort decreases substantially over time, as a result both of the retirement of the “other vessels” fleet, which almost exclusively operated that métier in 2009, and the impossibility for the remaining beam trawlers and netters to modify their effort allocation towards an increased proportion of the “others” métier, when $\alpha = 0.0$. With fixed quota allocation (QA1) and with $\alpha > 0.0$, fishing effort increases over time in the eastern Channel, at the expense of the western Channel and the “others” métiers (Figure 1a). With flexible quota allocation (QA2 or QA3) and with $\alpha > 0.0$, fishing effort decreases, except for the “others” métiers when $\alpha > 0.6$ (Figure 1b, c). The overall profit increases (Figure 2a), and the time dynamics of both QHO’s economic return and OLP depend on the quota allocation and fleet-behaviour mechanisms (Figures 2b, c).

The eastern Channel plaice spawning-stock biomass (SSB) increases over time, except under transferable quotas and economically driven fleet behaviour (Figure 3a), and the SSB of both western Channel stocks increases for all scenarios (Figure 3b, d). The landings decrease for eastern Channel plaice (Figures 3e), increase for western Channel plaice (Figure 3f), but their dynamics depend on the quota-allocation regime for western Channel sole (Figure 3h). The eastern Channel sole SSB and landings are subject to little variation over time (Figure 3c, g).

4.2. Quota-allocation regime

Compared with the fixed quota allocation scenario (QA1), certain changes transpire when quotas are transferable (QA2 and QA3). Métiers operating in the eastern Channel are less prevalent, whereas the “others” métiers show increased activity. The effort allocated to the western Channel is equivalent across the three quota allocation regimes (Figures 1a–c). Quota ownership hardly affects effort allocation.

The profit of beamers and small netters increases substantially (€50–150 million), a higher level than achieved by the large netters (€25 million; Figure 2a). With QHO-owned quotas (QA2), the QHO’s economic return is much larger (€200–250 million; Figure 2b). When quotas are fleet-owned (QA3), the “other vessels” fleet makes a large profit from leasing its TAC share to the other three (Figure 2a), and it plays a similar role under QA3 to a QHO under QA1 and QA2. The OLP is the largest (>€300 million) under QA1, and the smallest (<€20 million) under QA3 (Figure 2c).

The long-term SSBs of eastern Channel plaice and of both western Channel stocks decline, possibly below their respective B_{pa} values (Figures 3a, b, d), whereas eastern Channel sole SSB is hardly changed and stays above B_{pa} (Figure 3c). The long-term landings of eastern Channel stocks are hardly sensitive to the TAC-allocation regime, remaining at about or above TAC for eastern Channel plaice (Figure 3e), and at about 60% of the TAC for eastern Channel sole (Figure 3g). The long-term landings of both western Channel stocks are generally larger, and may exceed their respective TACs, especially when fleets become economically driven (Figures 3f, h).

4.3. Fleet behaviour

The following changes were observed when α increases from 0.0 to 1.0. Both western Channel métiers become less attractive (Figure 1). Under QA1 (Figure 1a), both eastern Channel métiers become increasingly attractive, and the amount of effort allocated to the “other métiers” remains stable but low. Under QA2 and QA3 (Figures 1b and 1c), the effort allocated to both eastern Channel métiers decreases slightly. In contrast, the fishing effort allocated to the “others” métier inflates, and exceeds its 2009 value when $\alpha > 0.5$.

The long-term economic profit of small netters and beam trawlers is comparable when fleet behaviour is traditional, but the small netters make the greatest profit as the fleets become increasingly opportunistic (Figure 2a). The QHO’s economic return is little affected by fleet behaviour under QA1, but it decreases substantially under QA2, as the fleets become more

economically driven (Figure 2b). Compared with the quota-allocation regime, fleet behaviour has a more-limited effect on the OLP (Figure 2c).
Under QA1, the long-term SSB of eastern Channel plaice and sole decreases, while the long-term SSB of both western Channel stocks increases (Figures 3a, b, c, d). These contrasting trends reflect the effort-allocation shift under the fixed quota-allocation regime (Figure 1a). Under QA2 and QA3, the long-term SSB of all stocks decreases close to or below B_{pa}, except for eastern Channel sole. This trend reflects the dramatic development of the "others" métier in relation to α under these quota allocation regimes, which offsets the reduction in the effort deployed in the western Channel (Figures 1b, c).

Overall, the long-term eastern Channel plaice landings increase slightly above the TAC (Figure 3e), whereas the average eastern Channel sole landings are hardly sensitive to fleet behaviour (Figure 3g). Under QA1, the long-term landings of western Channel plaice and sole gradually decrease below the TAC. In contrast, under QA2 and QA3, the long-term landings of both western Channel stocks generally increase to slightly above the TAC (Figures 3f, h). Although exceeding the TAC results in a tax compensation, the limited charge paid by these fleets is not sufficient to compromise their economic viability.

4.4. Overquota landing tax (OLT)

The following changes transpire when the OLT increases from 50% to 150% of fish price. Under QA1 and QA2, the overall profit of the fishery decreases (Figure 4a). When the OLT is set at the fish price or less, most of the profit is shared between small netters and beam trawlers. However, when the OLT is set above the fish price, only the large netters make a profit and remain in the fishery. Both the QHO's economic return (Figure 4b) and the OLP (Figure 4c) are greatest when the OLT is set at the fish price. All SSBs increase (Figures 5a–d), and all landings generally decrease (Figures 5e–h), especially when the OLT is greater than the fish price. Under QA3, profit, SSB, and landings are hardly sensitive to the OLT set, and the OLP remains low.

5. Discussion

The results presented here hopefully bring some elements to the discussion on whether and how rights-based management could be implemented in EU fisheries. The effect of a quota-allocation regime on both fleet and stock dynamics is shown to be generally sensitive to the assumptions made on fleet behaviour and OLT. Considering that, in reality, fleet behaviour is intermediate (e.g. Holland and Sutinen, 1999; Hutton *et al.*, 2004; Vermard *et al.*, 2008; Marchal *et al.*, 2009a), and OLT set at the fish price, our results suggest that allowing quota transfers would not have a great effect on either SSB or the landings of the main targeted stock (eastern Channel sole), but would drive the average SSB of eastern Channel plaice, western Channel sole, and western Channel plaice close to or even below B_{pa}, and landings from the same three stocks slightly above the TAC. Quota transfers, associated with an OLT set at the fish price, might therefore induce adverse effects on the conservation of eastern Channel plaice, western Channel sole, and western Channel plaice in this fishery, because fleets may accept to pay a charge for landing above the quota agreed for the stocks provided they make a profit from landing large quantities of the valuable eastern Channel sole. The average eastern Channel sole landings simulated never exceeded 60% of the TAC, which is linked to the mixed character of that fishery. Increasing the eastern Channel sole landings above that level would result in an increase in the landings of the other stocks, which are already above the TAC on average. Consequently, the OLP would also increase. Harvesting 60% of the eastern Channel sole TAC could therefore be considered as the maximum take that would allow economically viable exploitation of all stocks when the OLT is indexed to the fish price.

Two major benefits of allowing a flexible quota-allocation regime, as opposed to a fixed one, would be (i) a substantial increase in overall fishery profit, and (ii) a better match between catch and quota, as indicated by the considerably reduced OLP. The results given here also showed that the difference in OLP between TAC-allocation scenarios cannot be explained just by how much total landings aggregated over all fleets exceeded TAC, but rather by how much the individual fleets' landings exceeded their respective quota provision. Therefore, under the fixed quota-allocation scenario, the fleets that exceeded their quota provision would not have had the possibility to adjust their quota share in the following year to reduce the mismatch between their catch and the quota. These fleets would pay an OLP until fishing became economically non-viable. The discrepancy between catch and quota would persist during the whole projected period, because quota shares are never revisited while the catch composition changes dynamically over time. When quotas are transferable, the TAC allocation is adjusted annually in proportion to past profit, so the catch composition of the different fleets will better match their quota share, resulting in a reduced OLP. All fleets may still exceed, to some extent, their quota of eastern Channel plaice and both western Channel stocks, provided they make sufficient profit from landing the valuable eastern Channel sole.

Under a quota-transfer scenario, the results also indicate that small netters and beam trawler fleets would do most of the fishing. The profit achieved by beam trawlers is somewhat lower than that of small netters, primarily because of their relatively high operating costs. However, the higher costs per effort of these beam trawlers are offset by their productivity, which is still large enough to allow them to remain active. The results support the outcomes of other studies suggesting that quota transferability could induce a selection of the most cost-efficient fishing units and/or firms (Arnason, 1990; McCay, 1995; Kulmala *et al.*, 2007). With fleet ownership of catch quota, the "other vessels" fleet would considerably reduce activity, but would make a large profit from leasing quota to the other three fleets.

Changing the OLT would only have a substantial effect when quotas are owned by a QHO (QA1, QA2). Decreasing the OLT to half the fish price would push the SSB of eastern Channel plaice and of western Channel plaice and sole below B_{pa}, and the related landings above TAC, and this cannot be considered a viable management option. Increasing the OLT above fish price would further discourage landing above the TAC, which supports the conclusions of Marchal *et al*. (2009c). However, the conservation benefits would to some extent be offset by a substantial profit decrease, especially for beam trawlers and small netters. When the OLT is higher than the fish price, these fleets make a negative profit in the first simulation year (2010), which they cannot overcome in following years, until they eventually retire from the fishery. When quotas are owned by the fleets, the small netters and beam trawlers do not have to pay a rent to a QHO, which allows them to make a positive profit in 2010, and stay active in the fishery in subsequent years. Therefore, changing the OLT setting has little effect when quotas are owned by fishing fleets in this case study.

The conclusions of this investigation depend to some extent on a number of assumptions. Species other than sole and plaice contribute substantially to the economics of the Channel flatfish fishery, and these were implemented in the model as a single stock producing the same amount of fish every year, irrespective of fishing pressure. An alternative approach would have been to model the dynamics of other species using a general production model (Laurec *et al*., 1991). However, even that approach would require minimal biological information on these other species which, in many cases, would not be available for Channel stocks. It was further assumed that quota ownership was time-invariant, and also that total fishing effort per month was constant or null, depending on whether the anticipated short-term profit was positive or negative. In particular, we did not allow vessels to enter or exit the different fleets, or to buy/sell permanent quota allocations as a result of long-term choices. In reality, however, vessels may enter and exit fleets as a result of both short- and long-term economic performance and management restrictions (Pradhan and Leung, 2004). For instance, it is quite plausible that a number of vessels belonging to the “other vessels” fleet could change fleet or simply exit the fishery by selling quota shares as a result of their low fishing profit. However, it needs to be stressed that profit levels could be artificially inflated by subsidies, which could contribute to maintain economically inefficient vessels in the fishery (Mesnil, 2008). More-complex functions could have been used to model, for instance, investment/disinvestment dynamics (e.g. Hoff and Frost, 2008; Bastardie *et al*., 2010), but the data required to parametrize such functions were not available.

The model also restrictively implemented a management option (i.e. a TAC and an OLT) in the first year of the projections, without allowing any changes through the simulation period. One could contemplate adding a stock assessment module to the existing bioeconomic model, and updating both the TAC and the OLT as a result of the biomass levels being estimated based on a predefined harvest control rule. Also, the model used here is deterministic. Although the general results and trends derived from this deterministic model are informative in a context where the management system evaluated has never been implemented to date, a further step would be to run the simulations in a stochastic framework.

Despite these limitations, the results of this study do provide a usable framework to evaluate fisheries management strategies that build in quota allocation for mixed fisheries. Some of the results obtained could also illustrate, at least qualitatively, what could happen if rights-based management was implemented to regulate mixed fisheries consisting of a major target species and another group of less valuable bycatch species.

Supplementary material

Supplementary material summarizing the population and exploitation modules is available at the online *ICESJMS* version of this paper.

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Tables

Table 1. Parameters characterizing the growth, condition, natural mortality, recruitment and precautionary spawning biomass levels (B_{pa}) of sole (*Solea solea*) and plaice (*Pleuronectes platessa*) stocks (VIId and VIIe), and of other species, as implemented in the bioeconomic model.

Parameter		**Sole VIId**	**Sole VIIe**	**Plaice VIId**	**Plaice VIIe**	**Other species**
Number of age groups		11	12	10	10	1
Growth	L_∞	37.25	37.25	71.65	71.65	Not available
	K	0.35	0.35	0.23	0.23	Not available
	t_0	–1.61	–1.61	–0.83	–0.83	Not available
Condition factors	a	3.91×10^{-6}	3.91×10^{-6}	1.03×10^{-5}	1.03×10^{-5}	1.00
$W(\text{kg}) = aL(\text{cm})^b$	b	3.26	3.26	3.02	3.02	0.00
Natural mortality	M	0.10	0.10	0.10	0.12	Not available
Recruitment	R	2.35×10^{7}	4.15×10^{6}	1.70×10^{7}	4.58×10^{6}	2.25×10^{8}
Precautionary biomass (t)	B_{pa}	8 000	2 800	8 000	2 500	Not available

Table 2. Selectivity parameters for sole (*Solea solea*) and plaice (*Pleuronectes platessa*) used in the netter bi-normal selection curve (Madsen *et al*., 1999) and the beam trawl logistic curve (Rijnsdorp *et al*., 1981, and van Beek *et al*., 1983).

Gear	**Selectivity parameter**	**Sole**	**Plaice**
Net	Location of primary mode	3.27	2.58
	Spread of primary mode	0.18	0.24
	Location of secondary mode	3.59	3.25
	Spread of secondary mode	0.65	0.49
	Scaling constant	0.32	0.32
	Mesh size (cm)	10	10
Beam trawl	Selection factor	3.30	2.24
	Selection range	4.30	3.66
	Mesh size (cm)	8	8

Table 3. List of the five métiers and associated target factors implemented in the exploitation submodel.

Gear	**Fishing area**	**Métier code**	**Target factor**		
			Sole	**Plaice**	**Others**
Fixed net	Eastern Channel	1	0.35	0.10	0.01
	Western Channel	2	0.05	0.03	0.04
Beam trawl	Eastern Channel	3	0.29	0.25	0.01
	Western Channel	4	0.10	0.22	0.02
Other gear	Eastern and western Channel	5	0.22	0.40	0.92

Table 4. Proportional quarterly effort by métier (%) for small netters, large netters, beam trawlers, and the other vessels fleet, at the start of the simulations (for métier codes, see Table 3).

Fleet	**Quarter**	**Proportional effort per métier**				
		1	**2**	**3**	**4**	**5**
Small netters	1	0.71	0.28	0.00	0.00	0.01
	2	0.78	0.14	0.00	0.00	0.08
	3	0.73	0.25	0.00	0.00	0.02
	4	0.69	0.30	0.00	0.00	0.01
Large netters	1	0.29	0.71	0.00	0.00	0.00
	2	0.56	0.44	0.00	0.00	0.00
	3	0.45	0.55	0.00	0.00	0.00
	4	0.37	0.63	0.00	0.00	0.00
Beam trawlers	1	0.00	0.00	0.39	0.61	0.00
	2	0.00	0.00	0.27	0.61	0.12
	3	0.00	0.00	0.36	0.64	0.01
	4	0.00	0.00	0.28	0.56	0.16
Other vessels	1	0.00	0.03	0.01	0.00	0.96
	2	0.01	0.03	0.01	0.00	0.95
	3	0.00	0.02	0.01	0.00	0.97
	4	0.00	0.01	0.01	0.00	0.98

Table 5. TAC and landing price of the Channel sole (*Solea solea*) and plaice (*Pleuronectes platessa*) stocks. The average price, weighted by landings, of the other species caught in the Channel is also shown.

Management stock	**TAC (t)**	**Price (€ kg^{-1})**
Eastern Channel sole	6 593	10.32
Western Channel sole	765	10.32
Channel plaice	5 050	1.71
Other Channel species	Not available	1.80

Figures

Figure 1. Fishing effort by métier at the end of the 20-year projection period (year 2028), relative to *status quo* fishing effort (year 2009), as a function of the fleet behaviour strategy (α represents the *x*-axis) and of the three TAC-allocation scenarios (a) QA1, (b) QA2, and (c) QA3. The overquota landing tax (OLT) is set to the fish price for all stocks.

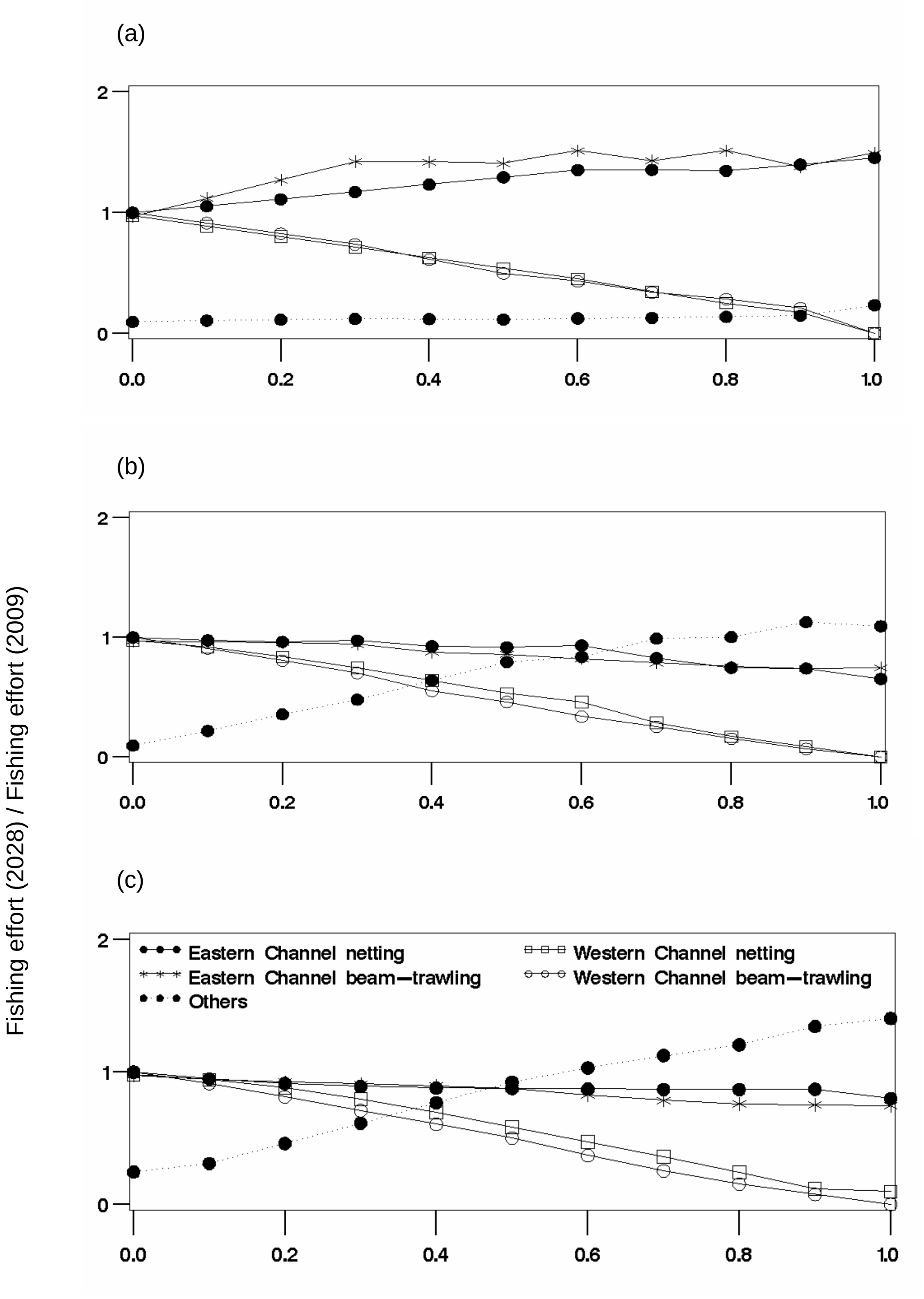

Figure 2. Projections of (a) annual profit (in million euros) by fleet, (b) annual economic return for the QHO, and (c) annual overquota landing payment (OLP), averaged in the short term over the period 2009–2013 (left bar of each pair) and in the long term over 2014–2028 (right bar of each pair). Each pair of bars represents a combination of a TAC-allocation scenario (QA1, QA2, or QA3) and a fleet-behaviour strategy (static, $\alpha = 0.0$; intermediate, $\alpha = 0.5$; fully economics-driven, $\alpha = 1.0$), with overquota landing tax (OLT) set to the fish price.

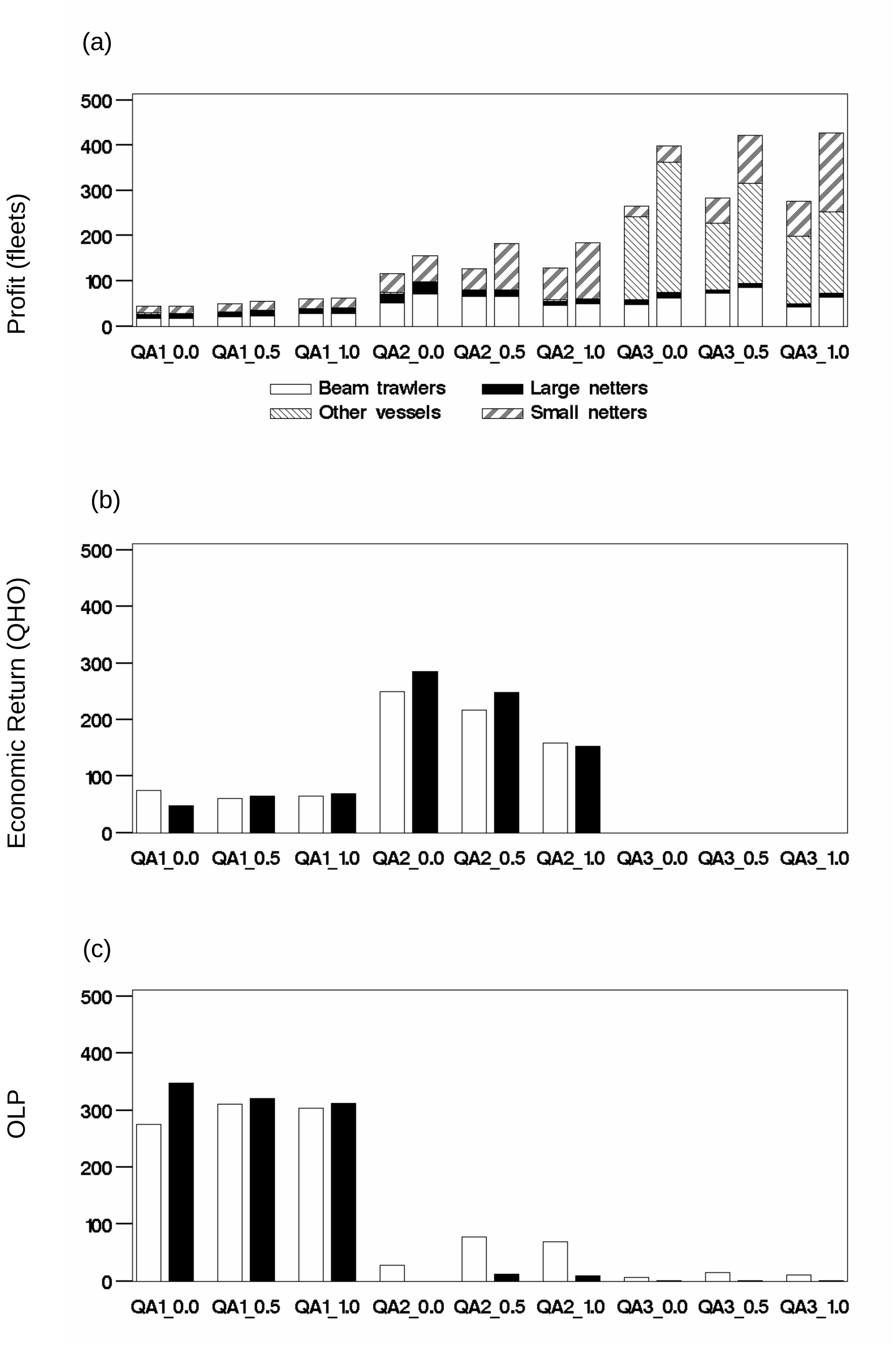

Figure 3. Projections of (a, b, c, d) the ratio between SSB (at 1 January of each fishing year) and B_{pa}, and of (e, f, g, h) the ratio between annual landings and TAC in the short term (2009–2013, white bars) and the long term (2014–2028, black bars), for (a, e) eastern Channel (VIId) plaice, (b, f) western Channel (VIIe) plaice, (c, g) eastern Channel (VIId) sole, and (d, h) western Channel (VIIe) sole. Each pair of bars represents a combination of a TAC-allocation scenario (QA1, QA2, or QA3) and a fleet-behaviour strategy (static, $\alpha = 0.0$; intermediate, $\alpha = 0.5$; fully economics-driven, $\alpha = 1.0$), with overquota landing tax (OLT) set to the fish price.

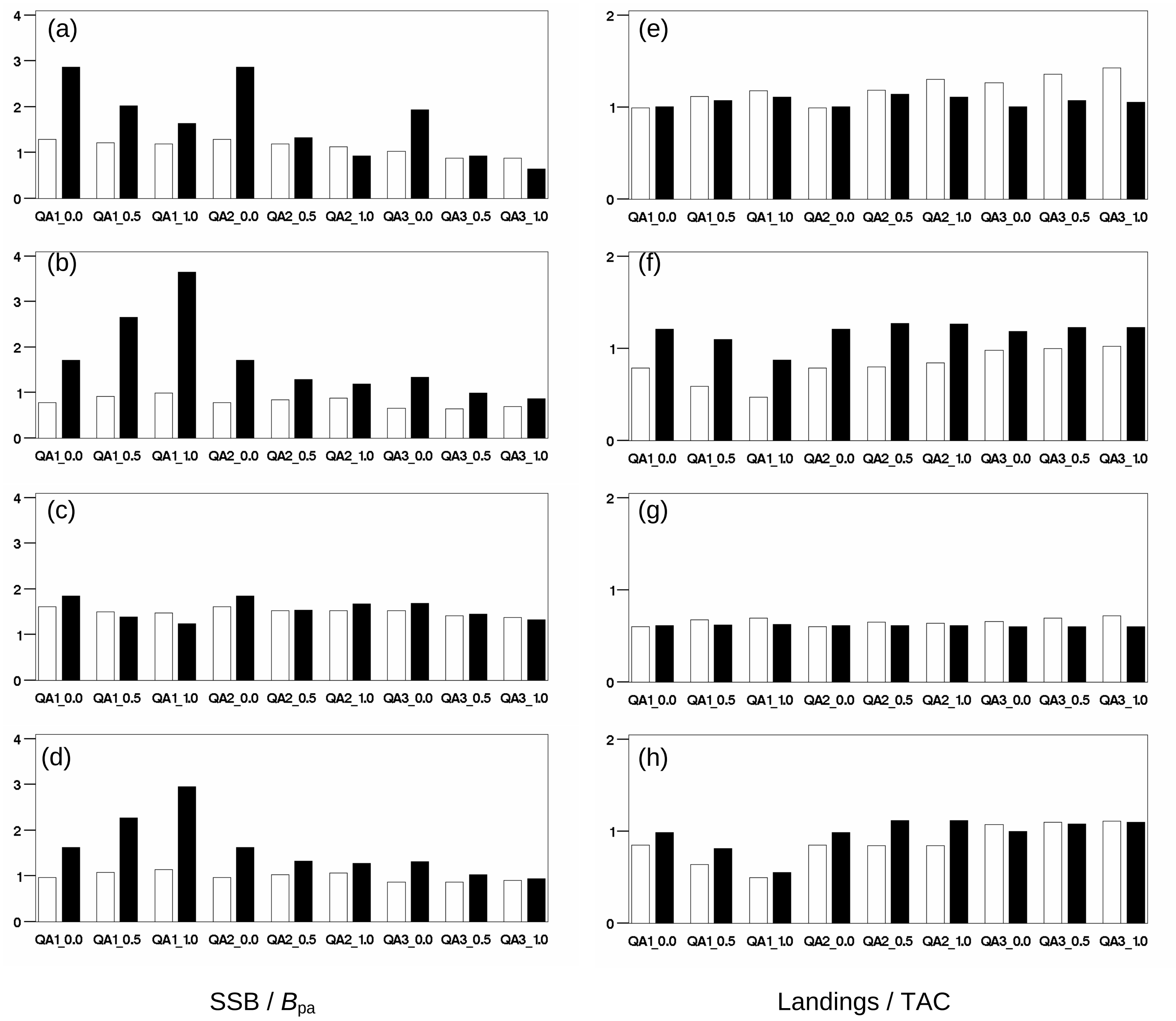

Figure 4. Projections of (a) annual profit (million euros) by fleet, (b) annual economic return for the QHO, and (c) annual overquota landing payment (OLP), averaged in the short term over the period 2009–2013 (left bar of each pair) and in the long term over 2014–2028 (right bar of each pair). Each pair of bars represent a combination of a TAC-allocation scenario (QA1, QA2, or QA3) and overquota landing tax (OLT; 0.5×, 1.0×, and 1.5× fish price) with intermediate ($\alpha = 0.5$) fleet behaviour.

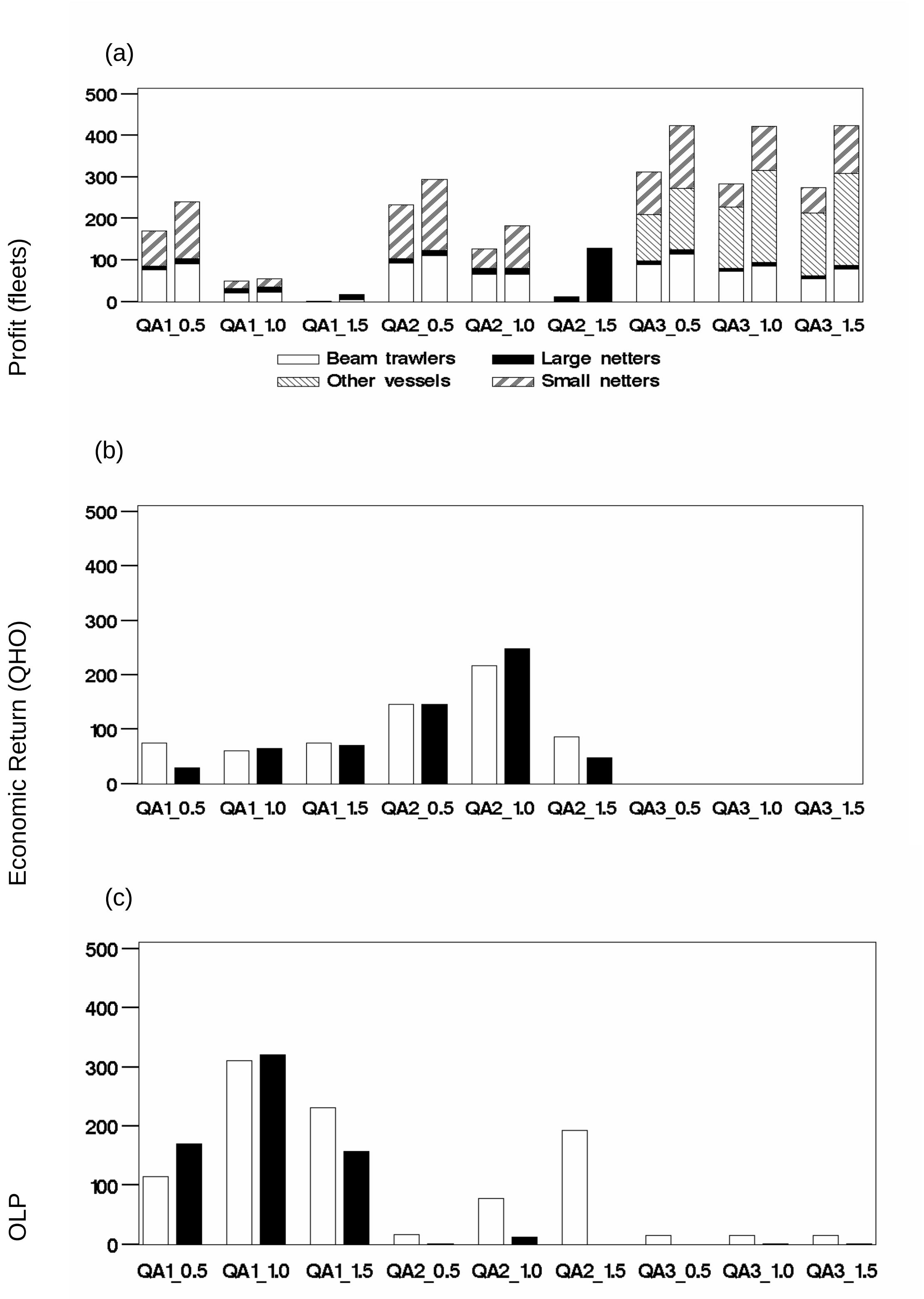

Figure 5. Projections of (a, b, c, d) the ratio between SSB (at 1 January of each fishing year) and B_{pa}, and of (e, f, g, h) the ratio between annual landings and TAC in the short term (2009–2013, white bars) and the long term (2014–2028, black bars), for (a, e) eastern Channel (VIId) plaice, (b, f) western Channel (VIIe) plaice, (c, g) eastern Channel (VIId) sole, and (d, h) western Channel (VIIe) sole. Each pair of bars represent a combination of a TAC-allocation scenario (QA1, QA2, or QA3) and overquota landing tax (OLT; 0.5×, 1.0×, and 1.5× fish price) with intermediate ($\alpha = 0.5$) fleet behaviour.