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# Endogenous Fishery Management in a Stochastic Model: Why Do Fishery Agencies Use TACs Along with Fishing Periods?

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**Abstract** This paper seeks to explain the circumstances under which using total allowable catch (TAC) as an instrument to manage a fishery along with fishing periods may be of interest from a regulatory point of view. The deterministic analysis by Homans and Wilen (J Environ Econ Manag 32:1–21, 1997) and Anderson (Ann Oper Res 94:231–257, 2000) is thus extended to a stochastic scenario where the resource cannot be measured accurately. The resulting model is solved numerically to find the optimal control rules in the Iberian sardine stock. Three relevant conclusions can be highlighted from simulations: first, the greater the uncertainty regarding the state of the stock, the lower the probability of the fishery being closed before the end of the fishing period. Second, the use of TACs as a management instrument in fisheries that are already regulated by fishing periods leads to: (i) an increase in the optimal season length and harvests, especially for medium and high numbers of licences; (ii) improved biological and economic variables when the fleet is large; and (iii) extinction risk for the resource being eliminated. Third, the regulator would rather select the number of licences than restrict the season length.

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## 1 Introduction

Since the seminal paper by Homans and Wilen (1997), endogenous fishery management literature has considered the regulatory process to be divided into two stages. In the first stage a target harvest quota is chosen to ensure stock safety. In the second stage managers choose one instrument to meet the harvest target. Season length is the instrument analysed by Homans and Wilen in their paper. Anderson (2000) expands this analysis by incorporating disaggregated vessel behaviour and comparing the effects of the use of trip limits or aggregate quotas with fishing periods. He shows that the same harvest target can be implemented using different "pure" strategies based on the use of only one instrument.

However, fishery management agencies regulate the real world using a mix of instruments simultaneously: gear restrictions, minimum sizes, area closures, fishing periods (season length) and total alloweble catches (TAC) by areas or individual vessel quotas (IVQ). For instance, the International Pacific Halibut Commission establishes fishing periods for each regulatory area of the fishery and a TAC for halibut in fishing periods for all areas (IPHC 2009). Each area is closed when the TAC is reached or the fishing period is over. In the same way, the European Commission has controlled the number of fishing days alongside other effort control measures since the year 2000 (see EC Regulation 1288/2009).

This paper seeks to determine the circumstances under which using TACs as an instrument to manage a fishery along with fishing periods may be of interest from a regulatory point of view. We extend the deterministic analyses by Homans and Wilen (1997) and Anderson (2000) to a stochastic scenario where the resource cannot be measured accurately (Clark and Kirkwood 1986) in order to answer this question. The regulatory process is also divided into two stages in our model. A target harvest is chosen by the regulator in the first stage. However, unlike Homans and Wilen (1997), we assume that the fishery manager does not know the real state of the stock when target harvest is fixed. As in Clark and Kirkwood (1986), this stock uncertainty arises from inaccurate stock estimations. In the second stage, daily quotas (or trip limits), fishing periods (the overall limits on the fishing season) and TACs can be use simultaneously as instruments to meet the target harvest.

Following Anderson (2000), we also include a disaggregated vessel analysis and intra-seasonal stock dynamics. We introduce a stochastic variable—daily fishing opportunities or luck—to reproduce the heterogeneity observed in both the daily harvest and the days per season at vessel level. In particular, we consider that on each day individual vessels, after observing the realisation of the daily fishing opportunity, choose whether to participate or not in the fishery. Participating vessels select the daily use of their capacity. Vessels may change capacity from season to season based on expected net returns over the future season. Finally, we allow vessels to exit. Neither the fishery manager nor individual vessels know the real state of the stock when exit and capacity decisions are taken. However, the real state of the stock is learned once the season starts.

The fishery management problem is solved taking into account intra- and inter-seasons decision by individual vessels. Managers commit to control rules that implement the optimal harvest target policy taking into account the expected future response of the industry. This response depends, all else being equal, on the specific combination of instruments chosen to implement the harvest target. In this sense, the model generates individual vessel behaviour endogenously, as a function of state variables and the policy instruments. Taking into consideration this optimal behaviour by individual agents, we find the optimal control rule used by the fishery manager for selecting the *ex-ante* target harvest. In this sense, our fishery management problem can be considered as an endogenous stochastic optimisation problem which can be computed numerically.[1]

The model is used to compare the relative advantages of two different management regimes: regimes that combine season length and daily individual quotas and regimes that combine season length, daily individual quotas and TACs. We find, that by introducing uncertainty into an endogenous model we help to show that instruments that are equivalent in a determinist endogenous model prove to have operational differences under uncertainty. TACs and fishing periods are not equivalent. In particular, the envisaged *ex-ante* harvest target and the true *ex-post* harvest implemented by using fishing periods will be different in our model, as the number of days on which each vessel decides to participate in the fishery and the intensity of use of the individual capacity both depend on the real state of the stock. The extend of this deviation, all else being equal, increases with the stock size.

Therefore, combining TACs with fishing periods is not superfluous in an uncertainty scenario. If the management regime introduces TACs the *ex-post* harvest deviation will be truncated at a certain maximum. Regardless of the real state of the resource, harvest cannot be greater than the *ex-ante* harvest target as the fishery is closed when the TAC is taken (or the fishing period is over). We find that the combination of the two instruments always reaches higher expected escapements. Moreover, if the number of vessels is large enough and the fishery is regulated without TACs, extinction is feasible.

Another interesting feature of our model is that with inaccurate stock estimations and large numbers of vessels, combining effort control (fishing periods) with harvest control (TACs) is the best regulatory choice. However, effort control (fishing periods) without harvest control is the best regulatory choice in the case of small numbers of vessels.

This result extends previous findings in the literature on fishery instrument choice under uncertainty (see Hannesson and Steinshamn 1991; Quiggin 1992; Danielsson 2002; Weitzman 2002; and Kompas et al. 2008). It is assumed in this literature that two (independent) sources of uncertainty exist: uncertainty in the stock recruitment relationship and uncertainty in the catch effort relationship. The optimal instrument depends on the relative size (the variance) of each source of uncertainty. Danielsson (2002) finds that in a single period model the greater the variability is in the catch-effort relationship relative to the stock recruitment, the greater the comparative advantage of harvest controls is relative to effort controls. Kompas et al. (2008) extend Danielssons' results to a fully optimal dynamic model.

Our results show that the relative size of the (the variance of) of each type of uncertainty is an endogenous variable induced by the regulatory regime. The greater the number of vessels (licences) and the greater the trip limit, the greater the variance of variability in the catch-effort relationship is relative to the stock recruitment, and therefore the greater the comparative advantage of combining harvest controls (TACs) with effort controls (fishing periods and trip limits) is.

Why is combining instruments the best choice when uncertainty arises from inaccurate stock estimations? The answer can be found in literature on fishery management under uncertainty. Reed (1979) concludes that when stock uncertainty comes exclusively from the stock recruitment relationship, the optimal policy is to allow constant escapement in every period

[1] As Arnason (2000) points out, endogenous optimisation fishery models can provide the necessary link between realistic fishery management measures and the development of the fishery. Moreover, increases in computing speed have made the use of this class of model feasible in practice.

and extinction never occurs. Clark and Kirkwood (1986) show that when managers cannot perfectly measure current stock the optimal policy is no longer the constant escapement rule, and in their model extinction is possible. Sethi et al. (2005) point out that extinction is only possible if there is such extreme miscalculation in stock measurement that the policy sets the harvest too high and drives the resource to extinction.

Our stochastic endogenous model can be seen as a framework that studies which combinations of instruments allow the optimal policy to be implemented when (i) stock uncertainty arises from inaccurate stock estimations and (ii) uncertainty in the catch effort relationship is endogenously generated by the behaviour of individual vessels, as a function of state variables and policy instruments (a Ramsey problem).

When the number of licences is decided, even in the deterministic case, it is not always possible to implement the first best policy. If the number of vessels is high, management regimes without TACs call for higher catches than the first best policy. Moreover, when the stock size is large the potential measurement error can be significantly large and the optimal fishing period rules call for longer seasons. Higher stocks also induce vessels both to participate on more days and to harvest more per day. As a result, escapement is lower than in the optimal first best policy. Moreover, if the number of vessels is large, extinction is possible. Therefore, in the case of fisheries with a large number of vessels, combining TACs with fishing periods calls for higher escapements and implementing best policies.

The rest of the paper is organised as follows. Section 2 builds upon Homans and Wilen (1997) and Anderson (2000) to establish an endogenous stochastic regulated restricted-access fishery management model. The optimal feedback policy is characterised in Sect. 3. Section 4 shows the strategy for numerically solving the model applied to the Iberian sardine stock. The results are illustrated in Sect. 5. Section 6 concludes.

## 2 A Regulated Restricted-Access Fishery

We build upon Homans and Wilen (1997) and Anderson (2000) to establish an endogenous regulated restricted-access fishery management model. Despite the fact that the number of vessels in the fishery is given, the overall "industry fishing effort" is an endogenous variable. Individual vessels adjust their capacity (adjustments in horsepower, length and hold capacity) from season to season based on the anticipated of both the biomass level and the regulations expected to be set by the agency. This capacity choice determines the amount of individual daily fishing effort (amount of labor, fuel, etc.) and the number of days on which each vessel will be in the fishery. Therefore, for a given season length and a trip limit, it can be shown that daily fishing effort and the overall number of fishing days devoted to the fishery by each vessel form an endogenous variable that depends on whether or not TACs are used along with fishing periods.

### 2.1 Industry Behaviour

As in Anderson (2000) we use a discrete model rather than a continuous one. Assume that the daily number of fish harvested by each vessel is given by

$$h_{d,t} = \xi_{d,t}^{1-\gamma}\theta k_t^{\alpha} e_{d,t}^{\gamma} X_{d,t}, \tag{1}$$

where subscripts $d$ and $t$ denote day and season, respectively. $\theta$ is a catchability parameter, $k_t$ is the individual vessels fishing capacity or power, $e_{d,t}$ is a measure of the daily use of fishing

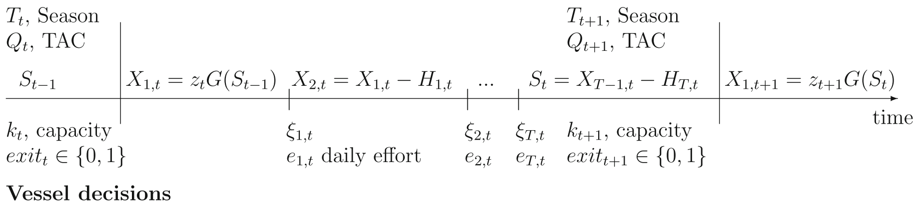


**Fig. 1** Vessel and regularor decisions

capacity, $X_{d,t}$ denotes the biomass, and $\xi_{d,t}$ is a i.i.d. stochastic variable that represents luck and/or fishing opportunities.[2] All vessels face the same value of $\xi_{d,t}$.

As in Homans and Wilen (1997) and Anderson (2000), the fishing capacity or power of individual vessels, $k_t$, is considered to be variable from season to season but fixed within each season. However, the daily use of this capacity depends on the stock size, $X_{d,t}$, and on luck, $\xi_{d,t}$. After observing the daily fishing opportunity, each vessel decides whether or not it will operate or not and what its daily effort, $e_{d,t}$, will be. This individual behavior leads daily captures to an aggregate level of $H_{d,t}$. Between seasons, each vessel chooses its capacity for the next season and the regulator selects the season length, $T$, and the TAC, $Q$, if any, for the next season taking into account the number of vessels $n^v$ and the daily limit per vessel, $\overline{h}$. We also allow vessels to exist in the fishery. Furthermore uncertainty regarding stock measurments is considered between seasons in such way that the stock at the beginning of each season, $X_{1,t}$, depends on the escapement in the previous season, $S_{t-1}$ and a random variable $z_t$ which reflects uncontrollable environmental variability. Figure 1 describes the information set available for each agent between any two consecutive seasons.

### 2.1.1 Within-Season Daily Effort Choice

Consider that within the season $t$, the regulator introduces a daily catch limit or trip limit per vessel, $\overline{h}$.[3] Further, let $we_{d,t}$ be the daily real variable running cost measured in real terms.[4] The maximum daily net return of an operating vessel is given by

$$\pi^o_{d,t} = \max_{e_{d,t}} \xi_{d,t}^{1-\gamma} \theta k_t^{\alpha} e_{d,t}^{\gamma} X_{d,t} - we_{d,t},$$

$$s.t. \begin{cases} \xi_{d,t}^{1-\gamma} \theta k_t^{\alpha} e_{d,t}^{\gamma} X_{d,t} \leq \overline{h}, \\ \xi_{d,t}^{1-\gamma} \theta k_t^{\alpha} X_{d,t} \quad \text{is} \quad \text{given}, \end{cases}$$

where superscript $o$ stands for operating vessel. From the first order conditions of this optimisation problem, the daily effort function is found to be

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[2] Vessels may learn the daily fishing opportunity before the start of a fishing day by analysing objective variables such as altimetry and surface currents, sea surface and subsurface temperature, cloudless temperature, ocean colour or location of ocean eddies and fronts. In fact, there are private companies which offer fishermen satellite-based services to support fishing.On the other hand, it could be thought that $\xi$ could be autocorrelated in real world. If this were the case, daily harvest decisions would have to be taken by solving a dynamic optimisation problem. In order to simplify the framework we focus on the policy decision problems by assuming that $\xi$ is i.i.d.

[3] As in Anderson (2000), each day of fishing is analogous to a trip.

[4] This daily variable cost is given by the cost of freezing fuel consumption while using gear and other running costs.

$$e_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}) = \begin{cases} \xi_{d,t}\left(\frac{\gamma\theta k_t^{\alpha} X_{d,t}}{w}\right)^{1/(1-\gamma)} & \text{if} \quad \xi_{d,t}[\theta k_t^{\alpha} X_{d,t}\left(\frac{\gamma}{w}\right)^{\gamma}]^{1/(1-\gamma)} \leq \overline{h}, \\ \left(\frac{\overline{h}}{\xi_{d,t}\theta k_t^{\alpha} X_{d,t}}\right)^{1/\gamma} & \text{otherwise.} \end{cases}$$

When the daily harvest limit is not binding, $h_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}) < \overline{h}$, the daily harvest is equal to

$$h_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}) = \xi_{d,t}\left[\theta k_t^{\alpha} X_{d,t}\left(\frac{\gamma}{w}\right)^{\gamma}\right]^{1/(1-\gamma)}. \tag{2}$$

Note that there is an upper bound on the daily fishing opportunities for each day, $\xi_{d,t} \leq \overline{\xi}_{d,t}$, where the daily restriction set by the regulator affects the maximum daily harvest for fishermen. Formally, $\overline{\xi}_{d,t}$ satisfies $h_{d,t}(\overline{\xi}_{d,t}, k_t, X_{d,t}|\overline{h}) = \overline{h}$. Therefore,

$$\overline{\xi}_{d,t} = \frac{\overline{h}}{[\theta k_t^{\alpha} X_{d,t}(\gamma/w)^{\gamma}]^{1/(1-\gamma)}}. \tag{3}$$

### 2.1.2 *Within Season Daily Participation Choice*

We also assume that there is a daily fixed running cost of $c_f$, such that daily net returns are given by

$$\pi_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}) = \max\left\{\pi_{d,t}^{o}(\xi_{d,t}, \theta, k_t, X_{d,t}|\overline{h}) - c_f, 0\right\}.$$

This running cost can be interpreted as the opportunity cost of using the vessel in this fishery.

The existence of this operational cost implies that there is a lower bound on daily fishing opportunities, $\xi_{d,t} \geq \underline{\xi}_{d,t}$, where it is optimal not to participate (on this day) in the fishery. Formally, $\underline{\xi}_{d,t}$ satisfies

$$\pi_{d,t}(\underline{\xi}_{d,t}, k_t, X_{d,t}|\overline{h}) = (1-\gamma)h_{d,t}(\underline{\xi}_{d,t}, k_t, X_{d,t}|\overline{h}) - c_f = 0,$$

that is

$$\underline{\xi}_{d,t} = \frac{[c_f/(1-\gamma)]}{[\theta k_t^{\alpha} X_{d,t}(\gamma/w)^{\gamma}]^{1/(1-\gamma)}}. \tag{4}$$

### 2.1.3 *Within-Season Stock Dynamics and Total Harvest*

We also assume that there is a licence limitation scheme that restricts access to the fishery. Let $n^v$ be the number of vessels. Then, taking into account the individual daily harvest, the expected aggregated fishery harvest on day $d$ of season $t$ is given by

$$H_{d,t}(k_t, X_{d,t}|\overline{h}, n^v) = n^v\left[\int_{\underline{\xi}_{d,t}}^{\overline{\xi}_{d,t}} h_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}_t) f(\xi_{d,t}) d\xi_{d,t} + \int_{\overline{\xi}_{d,t}}^{\infty} \overline{h} f(\xi_{d,t}) d\xi_{d,t}\right],$$

where $f(\xi_{d,t})$ is the probability density function of the random variable $\xi_{d,t}$. Note that we introduce upper case against lower case notation to distinguish fleet variables from individual variables, respectively.

Let $T_t$ be the length of season $t$. Thus, the expected total season harvest for the fishery is determined by

$$H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v) = \sum_{d=1}^{T_t} H_{d,t}(k_t, X_{d,t}|\overline{h}, n^v),$$

where the intra-season stock dynamics are given by

$$X_{d+1,t} = X_{d,t} - H_{d,t}(k_t, X_{d,t}|\overline{h}, n^v) \quad \forall d = 1, \ldots, T_t, \tag{5}$$

and the stock size at the beginning of the season, $X_{1,t}$, is taken as given.

Note that the shorter the season, the higher the capacity that the vessel has to use to maintain the same level of harvest.

### 2.1.4 Between-Seasons Capacity Choice

At the beginning of each season, each vessel selects the capacity that maximises its expected season profits. That is, $k_t$ is the solution of

$$\max_{k_t \in [\underline{k}, \overline{k}]} \quad E_t \pi_t(k_t, X_{1,t}, T_t|\overline{h}) - p_k k_t,$$

where, $E_t$ denotes the expectations at the beginning of season $t$, $p_k$ is the capital rental price and the vessel's profits for the season are

$$\pi_t(k_t, X_{1,t}, T_t|\overline{h}) = \sum_{d=1}^{T_t} \pi_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}).$$

Note that we allow vessels to adjust their capacity each season as fast as they want but within the set $[\underline{k}, \overline{k}]$. These limitations in capacity can be understood as short-run technical restrictions which do not allow dramatic changes in capacity.

Note that expected seasonal profits for each vessel can be expressed as

$$E_t \pi_t(k_t, X_{1,t}, T_t|\overline{h}) = \sum_{d=1}^{T_t} \phi \left[ \int_{\underline{\xi}_{d,t}}^{\overline{\xi}_{d,t}} \left((1-\gamma) h_{d,t}(\xi_{d,t}, k_t, X_{d,t}|\overline{h}) - c_f\right) f(\xi_{d,t}) d\xi_{d,t} \right.$$
$$\left. + \int_{\overline{\xi}_{d,t}}^{\infty} \left( \bar{h} - w \left( \frac{\overline{h}_t}{\xi_{d,t} \theta k_t^{\alpha} X_{d,t}} \right)^{1/\gamma} - c_f \right) f(\xi_{d,t}) d\xi_{d,t} \right]$$

where $1 - \phi$ is the share of labour for crew remuneration in the net returns for the season.

The optimal investment rule of each vessel is determined by

$$\frac{\partial E_t \pi_t(k_t, X_{1,t}, T_t|\overline{h})}{\partial k_t} = p_k. \tag{6}$$

### 2.1.5 Industry Welfare and Exit Decisions

Given the existence of a seasonal fixed cost, $p_k \underline{k}$, we assume that vessels can choose to exit the fishery if the expected net revenues are not high enough to cover the fixed cost. Formally, the optimal exit decision rule of each vessel is given by

$$W(X_t|\overline{h}, n^v) = \max_{exit} \left\{ \Pi^i(k_t, X_{1,t}, T_t)|\overline{h}, n^v) - r k_t + \beta W(X_{t+1}|\overline{h}, n^v), 0 \right\} \tag{7}$$

When the optimal decision is to exit, vessels adopt the criterion that $exit(X_{1,t}, T_t|\overline{h}) = 1$.[5] $W(X_{1,t}, T_t|\overline{h})$ can be interpreted as the value of the vessel $i$ or the licence price. Since the fleet is composed of identical vessels, the total industry welfare can be calculated as $n^v W(X_{1,t}, T_t|\overline{h})$.

## 2.2 Behaviour of the Regulator and Between-Seasons Stock Dynamics

We assume that stock growth in each season is a function of the escapement at the end of the previous season, $S_{t-1}$, and a random variable which reflects uncontrollable environmental variability, $z_t$,

$$X_{1,t} = z_t G(S_{t-1}). \tag{8}$$

Escapement $S_{t-1}$, is defined as

$$S_{t-1} = X_{1,t-1} - H_{t-1}(k_{t-1}, X_{1,t-1}, T_{t-1}|\overline{h}_{t-1}, n^v). \tag{9}$$

We assume that the fishery manager observes the total harvest, the daily catches, and the total number of harvesting days of each vessel in the season without error. The fishery manager therefore enters the new season $t$ knowing the state of the escapement $S_{t-1}$. However, the manager does not observe $z_t$ when establishing the season length, $T_t$. This implies that the decision of the fishery manager is based on the expected state of the resource at the beginning of the season $EX_{1,t} = G(S_{t-1})$.

Selecting TACs or quotas in a deterministic context means choosing the total fishery captures for the season. In particular, for season $t$ the quota is

$$Q_t = H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v).$$

Moreover, quotas and fishing periods are equivalent whenever they both guarantee the same escapement at the end of the season, $S_t = G(S_t) - Q_t$, (see Anderson 2000). However, under uncertainty, the envisaged ex-ante harvest

$$E_t H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v),$$

and the true ex-post harvest

$$H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v),$$

will differ as the intensity of use of individual capacity depends on the real state of the stock, $X_{1,t} = z_t G(S_{t-1})$.

We analyse the effects of two types of regulatory body in this uncertain framework:

(a) Regulatory body I, where the fishery manager establishes only the season length, $T_t$, without setting any quota for the period. In this case fishing will be over in $T_t$ and total escapement is given by

$$S_t = X_t - H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v).$$

(b) Regulatory body II, where the fishery manager establishes the season length, $T_t$, and the quota,

$$Q_t = E_t H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v),$$

[5] Since we are assuming that all vessels are identical, in equilibrium the decision finally taken on whether or not to exit the fishery is the same for all vessels. In order to obtain results where some vessels decide to exit the fishery and others decide not to exit, some kind of heterogeneity among vessels would need to be included. That, however, lies outside the scope of this paper.

for the season. If the quota is reached before the end of the season, then the escapement is $S_t = X_{1,t} - Q_t$. However, if the quota is not reached before the end of the season, the escapement is $S_t = X_t - H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v)$.
Note that the quota is not selected optimally from the point of view of the fishery authorities with this kind of regulation. Yet it is selected in such a way that it is compatible with the expected harvest level for a given season length. If this were not the case the industry would not understand the objectives of regulation.[6]

Therefore, escapement at the end of the season is the result of individual decisions on both capacity use and the number of days of fishing during the season, which in turn depend on whether or not the regulatory body establishes a season quota. In particular, we set out numerically below that escapement is greater with a season TAC than without one for any number of vessels.

## 3 The Fishery Manager's Problem

This section sets out the problem facing the fishery manager. In order to capture the biological orientation of most real-world fishery regulatory bodies we assume, like Homans and Wilen (1997), that managers have a single goal. In particular we assume that the fishery manager's objective function is to maximise the discounted future harvest.[7]

We start by assuming that the fishery manager knows the real state of the stock. This allows us to compare optimal policies under each regulatory body with previous results from literature based on deterministic models. We show that given this objective function, season lengths are chosen to ensure stock safety. Then we extend the analysis to an uncertainty context where the fishery manager does not know the state of the resource.

### 3.1 Optimal Rules Without Uncertainty

In a deterministic world the fishery manager chooses the season length $T_t$ that maximises present value of future catches taking into account stock dynamics (Eqs. (8) and (9)), the capital investment condition (Eq. (6)) and the vessel exit decision (Eq. (7)).

The optimal regulation rule can be obtained in two steps as in the model of Homans and Wilen (1997) if there is a season length $T_t$ that implements any possible quota $Q_t$. In such a case, the optimal rule can also be obtained by first solving

$$\max_{\{Q_t, S_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t Q_t,$$
$$s.t. \quad S_t = G(S_{t-1}) - Q_t \tag{10}$$

Given this quota policy, $Q(X_{1,t})$, the fishery manager then uses the capital implementation condition (6) to find the optimal vessel capacity $k_t$. Then the optimal season length, $T_t$, is that which satisfies $Q_t(S_{t-1}) = H_t(k_t, G(S_{t-1}), T_t|\overline{h}, n^v)$.

6 Considering other regulations may be very interesting: for instance situations in which the managers do not commit to the regulation or more advanced regulatory bodies in which both season length and quota are selected optimally to maximise a social utility function. Nevertheless we do not analyse any of these alternatives because our aim is to show that including a quota (even it is not the optimal one) as well as a season length may improve the results of a fishery.

7 This aim is in the line with the target set by the 2002 Johannesburg Summit whic it was established that all depleted stocks should achieve maximum sustainable yield by 2015.

The solution of problem (10) is well known in the relevant literature (see Reed 1979) and in a deterministic world, implies a constant escapement.[8] The optimal season length rule $T_t(S_{t-1})$ implied by problem (10) is given by

$$\begin{cases} T_t(S_{t-1}) = 0 & \text{if } G(S_{t-1}) < S^*, \\ H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v) = G(S_{t-1}) - S^* & \text{if } G(S_{t-1}) \geq S^*. \end{cases} \tag{11}$$

This optimal rule is a *bang-bang* policy that consists of closing the fishery if the escapement is lower than a safety level $S^*$.

However when it is not feasible to find a season length $T_t$ that implements any possible quota $Q_t$, the fishery manager chooses the season length, $T(S_{t-1})$, by solving

$$V(S_{t-1}|\overline{h}, n^v) = \max_{T_t} H_t(k_t, S_t, T_t|\overline{h}, n^v) + \beta V(S_t|\overline{h}, n^v),$$
$$s.t. \begin{cases} \frac{\partial \pi_t(k_t, G(S_t), T_t|\overline{h}, n^v)}{\partial k_t} = p_k, \\ S_t = G(S_t) - H_t(k_t, G(S_{t-1}), T_t|\overline{h}, n^v), \end{cases}$$

Note that dynamic programming (DP) is used to write the fishery manager's problem and that escapement at the end of the previous period is the state variable of the DP equation. This DP equation cannot be solved analytically but it can be solved numerically for calibrated fisheries. We consider below how this can be done for the case of the Iberian sardine stock.

### 3.2 Optimal Rules Under Uncertainty

Let us start by assuming that the managers use regulatory body I (no TAC). First note that, as in Clark and Kirkwood (1986), escapement can be precisely measured at the end of each season. So the fishery manager chooses the season length, $T(S_{t-1})$, by solving the following DP problem

$$V(S_{t-1}|\overline{h}, n^v) = \max_{T_t^I} \int_{z_t} \left\{ H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v) + \beta V(S_t|\overline{h}, n^v) \right\} f(z_t) dz_t,$$
$$s.t. \begin{cases} \frac{\partial \int_{z_t} \pi(k_t, X_{1,t}, T_t|\overline{h}) f(z_t) dz_t}{\partial k_t} = p_k, \\ S_t = z_t G(S_{t-1}) - H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v), \end{cases} \tag{12}$$

where $f(z)$ is the probability density of the random variable $z$. Observe that the fishery manager takes into account that: (i) vessels choose capacity at the beginning of the new season; and (ii) escapement at the end of the season is a function of the random variable, $z_t$.

[8] Note that, this problem is equivalent to finding the optimal escapement trajectory that maximises $\sum_{t=0}^{\infty} \beta^t [G(S_{t-1}) - S_t]$ given the initial condition $G(S_{t-1})$. The Euler equation is $1 = \beta G'(S_t)$, which is a *bang-bang* policy, with constant escapement level at the point, $S^*$, where the inverse of the discount factor, $1/\beta$, equals the slope of the growth function, $G'(S^*)$.

When TAC's are used (regulatory body II),

$$V(S_{t-1}|\overline{h}, n^v) = \max_{T_t^{II}} \int_{z_t} \left\{ \min\left[H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v), Q_t\right] + \beta V(S_t|\overline{h}, n^v) \right\} f(z_t) dz_t,$$

$$s.t. \begin{cases} \frac{\partial \int_{z_t} \pi_t(k_t, X_{1,t}, T_t|\overline{h}) f(z_t) dz_t}{\partial k_t} = p_k, \\ S_t = z_t G(S_{t-1}) - \min\left\{H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v), Q_t\right\}, \\ Q_t = \int_{z_t} H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v) f(z_t) dz_t, \end{cases} \tag{13}$$

Note that under regulatory body II, the envisaged quota must be consistent with the season length announced, the trip limit and the industry investment decisions. Finally, note that when the fishery manager uses TACs and fishing periods, the fishery sometimes closes before the season is over. That is, $T_t^c < T_t$ is such that

$$H_t(k_t, z_t G(S_{t-1}), T_t^c|\overline{h}, n^v) = Q_t.$$

Finally, under each regulatory body $i = I, II$, we check that vessels optimally decide not exit the fishery for the optimal season length rule, $T^i(S)$.[9] Formally, we solve

$$W^i(S_{t-1}, T_t^i|\overline{h}) = \max_{exit^i} \left\{ \int_{z_t} \left\{ \pi(k_t, z_t G(S_{t-1}), T_t^i(S_{t-1})|\overline{h}) - rk_t \right.\right.$$
$$\left.\left. + \beta W^i(S_t, T_{t+1}^i|\overline{h}) \right\} f(z_t) dz_t, 0 \right\},$$

$$s.t. \begin{cases} \frac{\partial \int_{z_t} \pi_t(k_t, X_{1,t}, T_t^i|\overline{h}) f(z_t) dz_t}{\partial k_t} = p_k, \\ S_t = z_t G(S_{t-1}) - H_t(k_t, z_t G(S_{t-1}), T_t^i(S_{t-1})|\overline{h}, n^v), \\ n^v = \overline{n}^v, \end{cases} \tag{14}$$

to check whether $exit^i(S_{t-1}, T_t|\overline{h})$ is zero for all $S_{t-1}$ and for the optimal season length rule, $T^i(S)$.

## 4 Numerical Simulations

In order to illustrate the effects of introducing ex-ante TACs, we apply the model to the Iberian sardine stock. This stock is located in European fishery areas VIIIc and IXa. European authorities do not set management targets for this stock and there is no TAC. However, the stock is managed by Portuguese and Spanish authorities through minimum landing size, maximum daily catch, fishing day limitations and closed areas. Suris (1993) addresses regulatory policies for this stock in a deterministic context.

In the following subsections, we describe the calibration of the model for the Iberian sardine stock and the code strategy followed to simulate the fishery behaviour.

[9] Since all the vessels are assumed to be identical, this condition is equivalent to assuming that the fleet size does not change from one period to another. In restricted fisheries such as the Iberian sardine fishery, failure to meet this condition means that the fleet will disappear in the future.

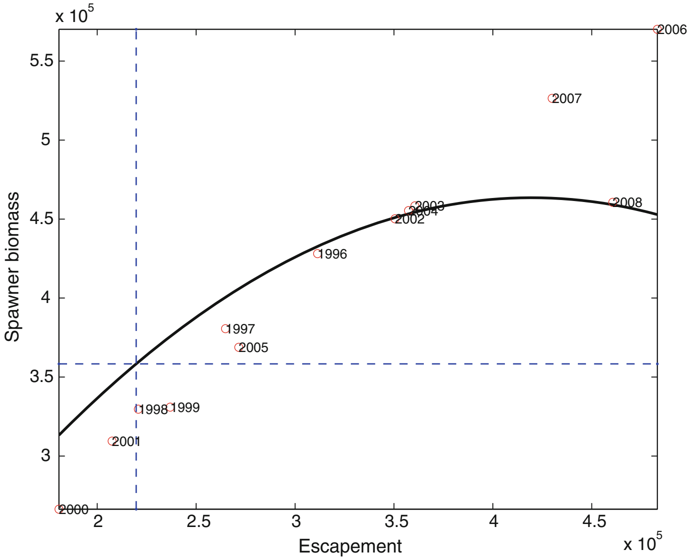


**Fig. 2** Escapement and spawner biomass. *Solid line* shows the estimated function. *Dotted lines* show the constant-escapement solution in a deterministic context. *Dotted lines* show optimal levels ($S^* = \widehat{L}[(1+\widehat{r}) - (1+\beta)]/2\widehat{r}$ and $X^* = S^*[(1+\widehat{r}) - (\widehat{r}/\widehat{L})S^*]$ associated with $\beta = 0.95, \widehat{r} = 1.2097$ and $\widehat{L} = 4.5934 \times 10^5$

## 4.1 Parameter Values and Functional Forms

We adopt the following parameter values and functional forms for our numerical computation:

1. **Biological dynamics**. As in Sethi et al. (2005), we assume a logistic growth function for stock. Under this assumption, the stock dynamics Eq. (8) can be expressed as

$$X_{t+1} = z_{t+1} S_t \left(1 + r - \frac{r S_t}{L}\right),$$

   where $r$ is interpreted as the intrinsic growth rate and $L$ is the carrying capacity of the resource.
   Data from the International Council for the Exploration of the Sea (ICES) data bank were used to work out the equation. Following the 2007 ICES assessment, we use 1996–2006 as the period for analysis.[10] The results of the estimation are $\widehat{r} = 1.2097$ and $\widehat{L} = 4.5934 \times 10^5$. Figure 2 illustrates the data and the estimation. The steady state spawner stock and harvest with $\beta = 0.95$ associated with the constant-escapement policy, ($S^* = \widehat{L}[(1+\widehat{r}) - \beta^{-1}]/2\widehat{r}$ and $X^* = S^*[(1+\widehat{r}) - (\widehat{r}/\widehat{L})S^*]$), are 219,676 and 357,734 Tn respectively. Finally, we assume that $z_t$ is an independent, stationary, uniformly distributed random variable of the following form:

$$z_t = 1 + (2u_t - 1)\varepsilon,$$

[10] The Stock assessment made by the ICES working group used indices from the Spanish March survey, covering Division VIIIc and Subdivision IXaN, and the Portuguese March survey, covering the remainder of Division IXa, added together without weighting, for the years 1996–2007.

**Table 1** Regression with robust standard errors

| ln h | Coef. | Std. err. | $t$ | $P > \|t\|$ | 95% conf. interval | |
|---|---|---|---|---|---|---|
| ln k | .9817207 | .0101138 | 97.07 | 0.000 | .9618965 | 1.001545 |
| year | −.1791843 | .0226093 | −7.93 | 0.000 | −.2235013 | −.1348673 |
| dm1 | .3299584 | .1123548 | 2.94 | 0.003 | .1097295 | .5501873 |
| dm2 | .3568161 | .1107017 | 3.22 | 0.001 | .1398275 | .5738048 |
| dm3 | .0675137 | .1174635 | 0.57 | 0.565 | −.1627287 | .2977561 |
| dm4 | .3057071 | .1097386 | 2.79 | 0.005 | .0906063 | .5208078 |
| dm5 | .7237725 | .1070695 | 6.76 | 0.000 | .5139034 | .9336415 |
| dm6 | .5203433 | .1061364 | 4.90 | 0.000 | .3123033 | .7283833 |
| dm7 | .2386561 | .1062406 | 2.25 | 0.025 | .0304118 | .4469004 |
| dm8 | .2601109 | .1069127 | 2.43 | 0.015 | .0505492 | .4696725 |
| dm9 | .4140819 | .1089408 | 3.80 | 0.000 | .2005449 | .627619 |
| dm10 | .4912853 | .1068017 | 4.60 | 0.000 | .2819412 | .7006294 |
| dm11 | .1998815 | .1164536 | 1.72 | 0.086 | −.0283815 | .4281446 |
| cons | 2.901477 | .1086673 | 26.70 | 0.000 | 2.688476 | 3.114478 |

Number of obs. = 15,243; F( 11, 15231) = 784.24; Prob > F = 0.0000; $R^2 = 0.3605$

where $u_t$ is drawn from a uniform distribution [0,1] and $\varepsilon$ is a parameter affecting the variance of the distribution of $z$. Since the maximum deviation of the data around the mean, $X_{t+1}/S_t\left(1+\widehat{r}-\frac{\widehat{r}S_t}{\widehat{L}}\right)$, is 40.5%, we decided to set $\varepsilon$ at 0.405.[11]

2. **Fleet capacity measurement**. Sardines are harvested by Spanish and Portuguese vessels. In northern Spanish waters, sardines are harvested by purse seiners. 51% of these purse seiners are licensed in Galicia (ICES 2007, Section 8.2.1). We calibrate the model to reproduce some stylised facts concerning the Galician sardine fleet. First, we estimate the daily harvest at vessel level using data from Pesca Galicia.[12] We construct panel data from daily data from January 1, 2007 to October 31, 2008. Our panel selects vessels that harvest at least 7,000 kilos per season.[13] The panel has 15,243 observations from 140 vessels. We estimate the following equation:

$$\log h_{id} = \delta Z_{i,d} + u_{id}$$

where $h_{id}$ is the sardine harvest of vessel $i$ on day $d$ and $u_{id} \backsim N(0, \sigma_u^2)$ represents a time-invariant unobserved individual heterogeneity. $Z_{i,d}$ denotes vector of exogenous variables in which a constant term—the gross registered tonnage (GRT), in logs—as a proxy of capacity, and monthly and year dummy variables are included. Table 1 shows the estimation results for the parameter vector $\delta$ using OLS.[14] Likewise note that elasticity of the capacity of 0.98 is obtained, which must be interpreted as the ratio $\alpha/(1-\gamma)$ taking into account the daily harvest function (1).

[11] Note that the method used to identify the level of uncertainty may exaggerate the variance as it is based on relatively few observations. Nevertheless, the values obtained are close to the one used in the literature.

[12] http://www.pescagalicia.com/.

[13] 7,000 kilos is the daily trip limit of this fishery set by the Spanish authorities.

[14] We also consider individual horsepower, size and vessel length. However, none of these variables is statistically significant. Note that only one season dummy (year) appears as we have data from two seasons.

**Table 2** Fleet stylized facts

| | |
|---|---|
| $D_1$ = Average harvest per day (Tn) | 1.91 |
| $D_2$ = Probability that daily harvest $< \overline{h}$ | 0.99 |
| $D_3$ = % of the average number of operating days per season | 0.43 |
| $D_4$ = Elasticity of the capacity | 0.98 |

*Source*: Own calculation for the Galician sardine fleeet using data from Pesca Galicia

3. **Parameters calibrated from the model**.
   The fishing opportunity variable, $\xi$, is assumed to follow a log normal distribution with $Log\xi - N(0, \sigma_\xi^2)$. The parameter $\sigma_\xi^2$ and the boundary values $\underline{\xi}$ and $\overline{\xi}$ are calibrated in such a way that the stylised facts on the fishery shown in Table 2 are reproduced. In particular, these three values can be obtained as the solution of the following three-equation system,

$$D_1 = \overline{h} \left\{ \int_{\underline{\xi}}^{\overline{\xi}} \frac{\xi}{\overline{\xi}} f(\xi)\, d\xi + \int_{\overline{\xi}}^{\infty} f(\xi) \right\} d\xi,$$

$$D_2 = \int_{-\infty}^{\overline{\xi}} f(\xi)\, d\xi,$$

$$D_3 = \int_{\underline{\xi}}^{\infty} f(\xi)\, d\xi.$$

   Note that the average daily harvest rule for calculating $D_1$, when the fleet harvests less than $\overline{h}$, is expressed as $\xi\overline{h}/\overline{\xi}$ taking into consideration (2) and (3). $D_2$ represents the probability that the daily harvest will not exceed the daily harvest cap $\overline{h}$. $D_3$ represents the probability of bad fishing opportunities that make it optimal not to participate (on that day) in the fishery optimal. So $D_3$ is approximated with the average of the % number of operating days per season.

Once the boundary values $\underline{\xi}$ and $\overline{\xi}$ have been calibrated, given a guess of the capacity return $\alpha$, the parameters $c_f, \theta$ and $\gamma$ can be calculated using the definitions of the boundary of $\xi$, Eqs. (3) and (4), and the elasticity of capacity (see Eq. (2)). That is,

$$c_f = (1-\gamma)\bar{h}\underline{\xi}/\overline{\xi},$$

$$\theta = \frac{[\bar{h}/\overline{\xi}]^{1-\gamma}}{Xk^{\alpha}(\gamma/w)^{\gamma}},$$

$$D_4 = \frac{\alpha}{1-\gamma},$$

where $X = 526{,}457$ Tn, $k = exp(3.4)$ GRT and $w = 1/0.9$ Tn are the 2007 biomass, average internal volume of vessels and average real cost of fleet sample, respectively.[15] Finally Eq. (6) is used to check whether the guess value used for $\alpha$ implements the capacity level.

Given all the parameters, it is possible to calculate the harvest path and simulate the intra season stock evolution using the dynamic Eq. (5). The average value of the daily harvest, $h_{d,t}$,

[15] Sardine prices per day remained quite consistent throughout 2007 at around 0.9 euros per kilo.

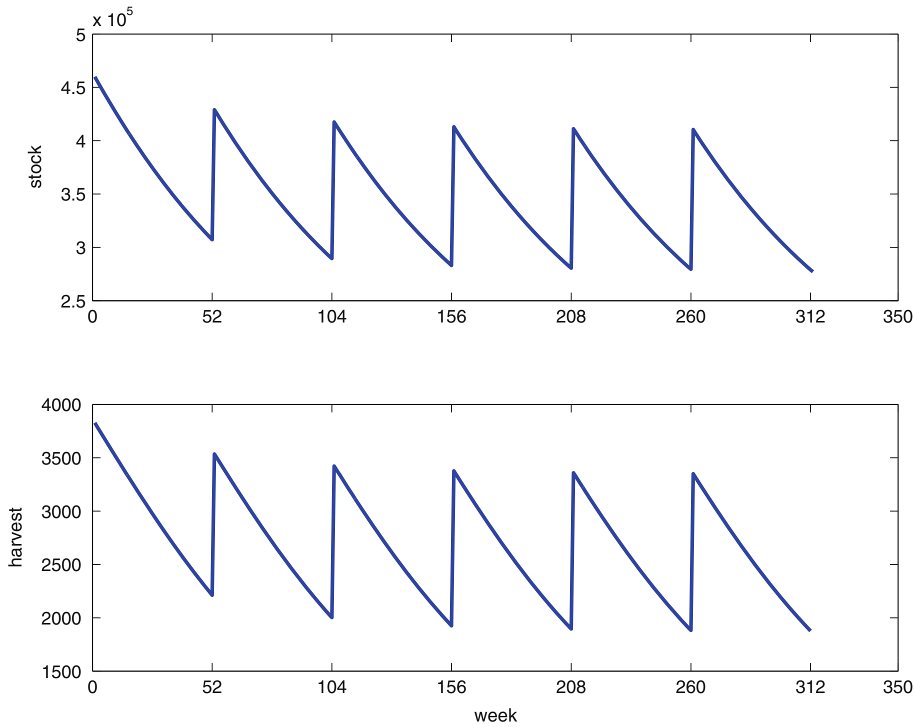


**Fig. 3** Intra and inter season dynamics with the calibrated parameters

and the fractions of restricted days are calculated to mimic the average data for the fishery throughout the season. The season length is set to reproduce the total captures of the 130 vessels in the sample. Figure 3 shows the inter and intra season harvest and stock dynamics for the parameters calibrated.

To close the calibration, we consider a discount factor $\beta = 0.95$ which has been used in applied fishery studies (Da Rocha et al. 2010 and Da Rocha and Gutiérrez 2011). As a rental capital price we use the associated discount rate, which is $1/\beta - 1$; that is $p_k = 5.26\%$. This value is between the rank used in other fishery studies (Bjørndal et al. 2004a,b and Bjørndal and Brasão 2006). The limits in the capital capacity are taken as $[\underline{k}, \overline{k}] = [0.85\times 30,\ 1.15\times 30]$ with 30 being the average internal volume of vessels of the sample measured in GRT. The capital share is taken as $\phi = 0.5$, which is in accordance with the % of net revenues accounted for by crew payments in the Iberian sardine fleet. The trip limit is taken to be equal to $\overline{h} = 7$ Tn which is the figure imposed by the Spanish authorities for the Iberian sardine.

Table 3 summarises the parameter values used for the benchmark model. Sensitivity analysis shows that results are qualitatively very robust to changes in the parameters of the model.

## 4.2 Simulation Strategy: Codes

Codes for simulating fishery behaviour have been written in Matlab. The simulation strategy for finding the optimal rules for the season $t$ follows algorithm below:

1. A fleet is defined by the number of vessels, $n^v$, the trip limit, $\overline{h}$, and the season length, $T$.

**Table 3** Model parameter calibration

| | | | |
|---|---|---|---|
| *Daily harvest parameters* | | | |
| $\theta$ | Catchability coefficient | $1.5241\times10^{-7}$ | Daily harvest estimation* |
| $\gamma$ | Daily effort returns | 0.1138 | $\alpha/(1-\gamma)=0.9817$ and investment rule (6)* |
| $\alpha$ | Capacity return | 0.87 | $\alpha/(1-\gamma)=0.9817$ and investment rule (6)* |
| *Technical fishery parameters* | | | |
| $\overline{h}$ | Daily trip limit | 7 | Spanish fishery autorities |
| $\sigma_\xi$ | Fishing daily opportunity | 0.7453 | Stylized facts from Galician fleet* |
| $\phi$ | Owner share | 0.5 | Galician fleet data* |
| *Growth resource parameters* | | | |
| $r$ | Stock growth rate | 1.2097 | Logistic growth function estimation** |
| $L$ | Carrying capacity of the stock | $4.5934\times10^5$ | Logistic growth function estimation** |
| $\epsilon_z$ | Stock uncertainty | 0.4050 | Uniform distribution estimation** |
| *Factor prices* | | | |
| $c_f$ | Daily fix cost | 1.1186 | $c_f=(1-\gamma)\bar{h}\underline{\xi}/\overline{\xi}$ |
| $p_k$ | Capacity price | 5.26% | $p_k=1/\beta-1$ |
| *Discounting* | | | |
| $\beta$ | Discount factor | 0.95 | Da Rocha et al. (2010); Da Rocha and Gutiérrez (2011) |

* Data from Pesca Galicia
** ICES (2007)

2. The season length $T$ is partitioned into 52 weels. The following actions are performed for any value of $T$ and for each possible value of escapement $S_{t-1}$ and the state of the stock $z_t$, which implies a stock $X_{1,t}=z_tG\,(S_{t-1})$:
   (a) The daily harvests and profits functions, $h_{d,t}$ and $\pi_{d,t}$, are calculated for any $k_t$ using the value of $\overline{h}$.
   (b) The daily aggregate harvest, $h_{d,t}$ is calculated for any $k_t$ using the value of $n^v$.
   (c) The next daily stock is calculated by subtracting the daily aggregate captures from the initial stock.
   (d) The season profits of each vessel, $\pi_t$, are calculated by adding up the profits for the $T$ weeks in which the season is open.
   (e) The investment problem for each vessel is solved at the beginning of the season. That is $k_t$ is calculated using (6) for the associated $X_{1,t}$, $T$, $n^v$ and $\overline{h}$.
   (f) The daily aggregate harvest and profit functions, $h_{d,t}$ and $\pi_{d,t}$, are recalculated for the optimal $k_t$ obtained from the investment problem.
   (g) The seasonal aggregated harvest and profit functions, $H_t$ and $\Pi_t$, are calculated from the daily functions.
3. For each combination of $n^v$ and $\overline{h}$, the optimal season lengths rule in each regime, $T^i(S_{t-1})$, is calculated by solving the corresponding Bellman equation (DP problems (12) and (13)).
4. Given the optimal season length, individual vessel profits are calculated for the whole season. Based on this result, each vessel decides whether or not to exit the fishery by solving the DP (14). It is verified that for each regime $i$, the exit function $exit(S_{t-1}, T_t|\overline{h})$ is zero.
5. When a TAC regime is considered the optimal season length, $T_t^{II}$, is replaced in the aggregate harvest function to calculate the TAC that closes the fishery,

$$Q_t = \int_{z_t} H_t(k_t, z_t G\left(S_{t-1}\right), T_t^{II})|\overline{h}, n^v) f(z_t) dz_t.$$

## 5 Results

The model establishes that the optimal season length is a function of the state of the resource and the combination of policy instruments selected to manage the stock (licences, trip limits and whether or not TACs are used). This section presents numerical simulations of the model to show the relationships between the variables.

The simulation results are presented in three parts. First we consider how different combinations of licences and trip limits affect the optimal season length. Secondly, we compare the effect of each regime body in biological and economic terms. And thirdly, we address the extinction issue.

### 5.1 The Season Length Rule

#### *5.1.1 Deterministic Model*

When there is no uncertainty regarding the state of the resource and there are no additional implementation restrictions, the optimal harvesting rule consists of constant escapement. This implies that the fishery has to be closed whenever $X_{1,t} = G(S_{t-1}) < S^*$. When $X_{1,t} = G(S_{t-1}) \geq S^*$ the fishery is open; then the optimal harvested is calculated as $H_t^* = G(S_{t-1}) - S^*$ and the resource dynamic is given by $X_{1,t+1} = G\left(X_{1,t} - H_t^*\right)$.

Alternatively, in an endogenous model where vessels take daily decisions, the optimal season length depends on other implementation restrictions. In particular, the optimal length for season $t$ is a function of the stock for a given number of licences, $n^v$, and the trip limit, $\overline{h}$; that is $T_t^*(X_{t,1}|n^v, \overline{h})$. Once the optimal $T_t^*$ is selected by the manager, the optimal total harvests are calculated as $H_t^*(k_t, X_{1,t}, T_t^*|\overline{h}, n^v)$ and the resource dynamics is given by

$$X_{1,t+1} = G\left[X_{1,t} - H_t^*(k_t, X_{1,t}, T_t^*|\overline{h}, n^v)\right].$$

Figure 4 illustrates how the optimal season length varies when the stock and number of licences change for a trip limit equal to the benchmark value $\overline{h} = 7$ in a deterministic scenario with respect to the stock.[16] The left-hand panel shows a 3D graph with the optimal season length (in weeks) for different combinations of stocks and number of vessels. It can be seen that as the stock of the resource and the number of licences increase, the optimal season length increases. The right-hand panel shows the combinations of stock and vessels that lead the fishery to different scenarios in terms of closure during the season: (i) the fishery never closes (red), (ii) the fishery never opens during the season (dark blue); (iii) the fishery closes at some moment in the season (light blue). The white dotted line shows the situation of constant escapement; below (above) the dotted line the constant escapement rule would imply the closure (opening) of the fishery. The results are quite intuitive. When the stock is high and the number of licences is low, fisheries can be open for the whole season because the total harvest is not high enough to close the fishery. By contrast, fisheries remain closed throghout the season regardless of the number of licences whenever the stock of the resource is below around 200 thousand tonnes. Nevertheless, there are small areas where the optimal endogenous model implies that a fishery is totally closed while the constant escapement policy would imply that it is partially open and vice versa.

[16] Simulations have been run assuming $\epsilon_z = 0$, all else being equal.

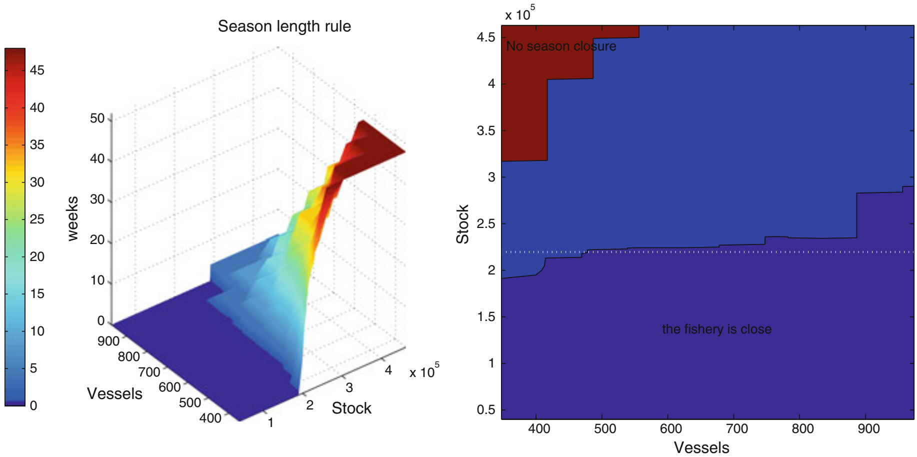


**Fig. 4** Deterministic model with respect to the state of the stock. *Left panel* $T(X_{t,1}, n^v|\bar{h} = 7)$ rule. *Right panel* $T$ rule versus constant-escapement rule (*white dotted line*)

To set the number of vessels in the fleet, we start by calculating the minimum number of vessels that, if they fish every day, would generate aggregate captures compatible with the harvest of the resource analysed. For the case of the Iberian sardine that number is 348. We denote this as a small number of vessels. In most cases, we run the simulations increasing this number of licences by 20% (medium number of vessels) and by 260% (large number of vessels).

Figure 5 compares the optimal solution for season lengths, harvests and escapements for different stocks with those implied by the constant-escapement solution (11) for the small number of vessels (panel a), for the medium number of vessels (panel b) and for the large number of vessels (panel c). For harvest and escapement, the constant escapement solution is shown by the blue doted line. Observe that when the number of licences is small (Fig. 5 panel a) the optimal solution differs from constant escapement because the harvest associated with the steady state solution cannot be captured due to the small capacity of the fleet. Because of this, from the point of view of the regulator, it is optimal to allow higher harvests and keep the fishery open for more time than in the constant escapement solution.

When the number of licensed vessels increases to a medium level (Fig. 5 panel b) the optimal rule is similar to the constant-escapement solution. Slight differences appear because the season length is not a continuous variable (it is set in weeks). Finally, when the number of vessels is very large (Fig. 5 panel c) the optimal rule cannot sustain the steady state solution of constant escapement. Indeed, if the fishery is open for a short period, the fleet harvests more than is desirable. In this case, the optimal rule may generate cycles: the fishery is closed for stocks higher than those from constant escapement and when it is open the harvest is higher than with constant escapement.

The right-hand panel of Fig. 4 summarises this information. Observe that for high levels of stock an increase in the number of vessels leads the regulator to close the fishery although there is no extinction risk. Likewise for stock levels below but near the constant escapement level the regulator may decide not to close the fishery if the number of vessels is small.

### *5.1.2 Uncertainty from Inaccurate Stock Estimations*

When stock uncertainty arises from inaccurate stock estimations the optimal policy is no longer a constant escapement rule (Clark and Kirkwood 1986). Moreover, Sethi et al. (2005)

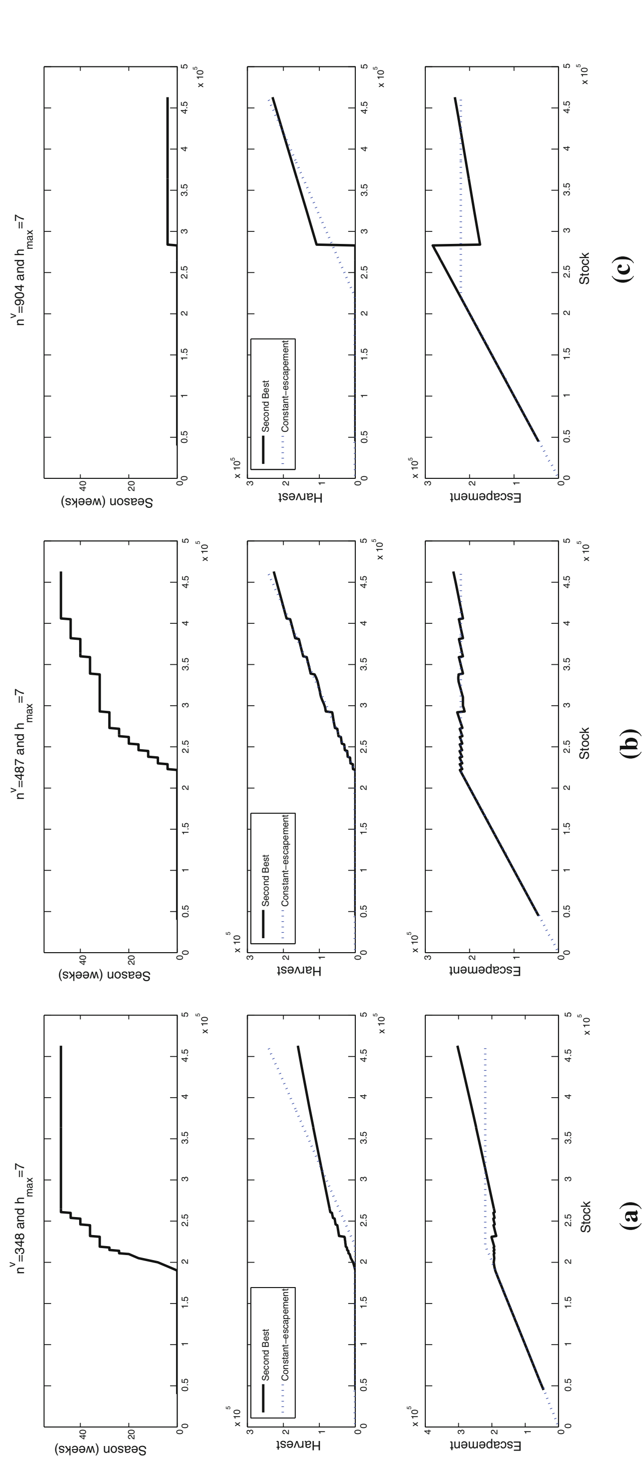


**Fig. 5** Optimal harvests, escapement and length seasons as function of stock. Deterministic model with respect to the state of the stock. **a** Small number of vessels, **b** medium number of vessels, **c** large number of vessels

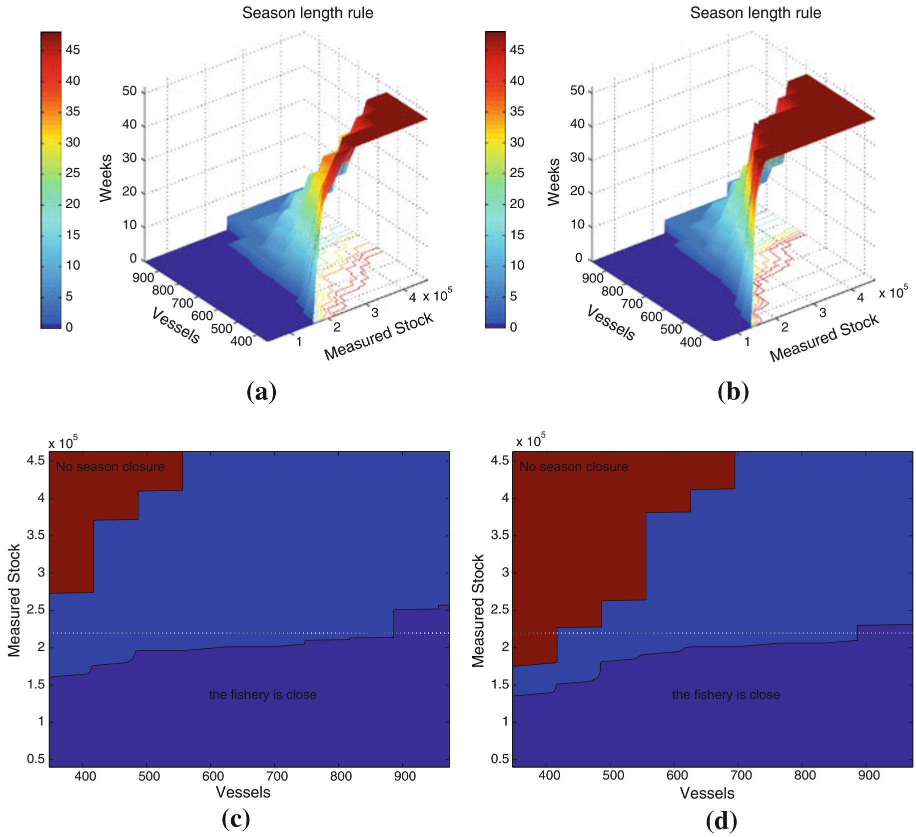


**Fig. 6** Model with uncertain stock. *Upper panel* $T(X_{t,1}, n^v|\overline{h} = 7)$ rule. *Lower panel* $T$ rule versus constant-escapement rule (*white dotted line*)

point out that "while optimal policy suggests lower escapement in the (biomass) middle range, it advocates higher escapement in the (biomass) last range". In order to check whether these results appear in our model, we compare the optimal rules with the constant-escapement solution assuming uncertainty regarding the state of the resource. Furthermore, we show that the optimal rules depend on whether or not TACs are considered as a management instrument.

Figure 6 mimics the results of Fig. 4 but considers an uncertain scenario with respect to the stock.[17] The left-hand panel shows the results when managers do not establish TACs for regulating the fishery (regulatory body I). The right-hand panel shows results assuming that fishery managers also establish *ex-ante* TACs (regulatory body II).

A comparison of the right-hand panel in Fig. 6 with Fig. 4 shows how much the results depend on uncertainty. It is clear that the greater the uncertainty regarding the state of the stock, the smaller the probability of closing the fishery is (the red area increases and the dark blue area decreases with uncertainty). Therefore, our results are along the same lines as Sethi et al. (2005). Furthermore, a comparison of the left-hand panel with the right-hand panel in Fig. 6 shows how much the results depend on TACs being considered an instrument. It is observed that using TAC as a management instrument increases the optimal season length.

[17] Simulations have been run assuming $\epsilon_z = 0.4050$, all else being equal. In Sect. 4.1, we explain how this value has been selected.

Figure 7 compares the optimal season lengths, harvests and escapements for different stocks under the two types of regulatory body analysed. Blue lines show regulatory body I (with TAC). Red lines show regulatory body II (without TAC). In particular, we show the optimal solutions for a small number of vessels (panel a), for a medium number of vessels (panel b) and for a large number of vessels (panel c). Note that under uncertainty, optimal harvests and escapement are calculated in terms of expectations. Therefore, the expected values under regulatory bodies I and II are different as both the optimal season length and the dynamics are different. Formally,

$$S_t^I = \int_{z_t} \left\{ z_t G(S_{t-1}) - H_t^I(k_t, z_t G(S_{t-1}), T_t^I(.)|\overline{h}, n^v) \right\} f(z_t) dz_t,$$

$$S_t^{II} = \int_{z_t} \left\{ z_t G(S_{t-1}) - \min \left\{ H_t^{II}(k_t, z_t G(S_{t-1}), T_t^{II}(.)|\overline{h}, n^v), Q_t \right\} \right\} f(z_t) dz_t.$$

Figure 7 reveals some important findings. First, as shown in Fig. 6, the optimal season length is greater when TACs are used as a management instrument than when they are not. This is true for any number of vessels and for any measured stock. The explanation is that when managers use TACs a longer fishing period may be set to cover unexpected poor fishing opportunities. In fishing opportunities are better than expected and vessels harvest more than expected, then the fishery is closed earlier, just when the TAC is exhausted. Second, when the number of vessels is large there are three easily identifiable stock intervals over which the season length rule is constant at different levels. This happens because it is not possible to implement continuous policies when the fleet is large. The discrete character of the season length leads to large variations in the harvest generating pulse (corner solutions) instead of continuous changes. Third, when the number of vessels is not large (panels a) and b)) the optimal harvest is larger and the escapement is lower without TAC than with TAC, especially for large measured stocks. Note that when regulators do not use TAC, season lengths are shorter than with TAC and vessels select higher capacities to maximise future profits. This implies that the fleet ends up fishing more and escapement decreases more than with TACs.

### *5.1.3 Trip Limits*

Finally, we analyse how changes in the trip limit parameter change the optimal season length. Figure 8 illustrates the effects of changes in parameter $\overline{h}$ during the fishery closure for different combinations of vessels and stock. This figure is similar to the right-hand panel in Fig. 4 but divided into two parts. The left-hand panel of Fig. 8 corresponds to the bottom part of the graph in the right-hand panel in Fig. 4 (stock from $1.5 \times 10^5$ to $3 \times 10^5$). The right-hand panel of Fig. 8 corresponds to the top part of the graph in the right-hand panel in Fig. 4 (stock from $3 \times 10^5$ to $4.6 \times 10^5$).

Figure 8 shows how the boundary for seasonal closures moves when trip limit parameter varies from the benchmark value $\overline{h} = 7$ (black boundary line) to $\overline{h} = 5$ (slash white boundary line) and $\overline{h} = 9$ (solid white boundary line). Note that upward movements in the boundary line means that the stock has to be higher to close the fishery for a given number of vessels. Rightward movements in the boundary line show that the number of vessels has to be higher to close the fishery for a given stock. The main result is that lower trip limits imply longer seasons with less probability of the fishery being closed.

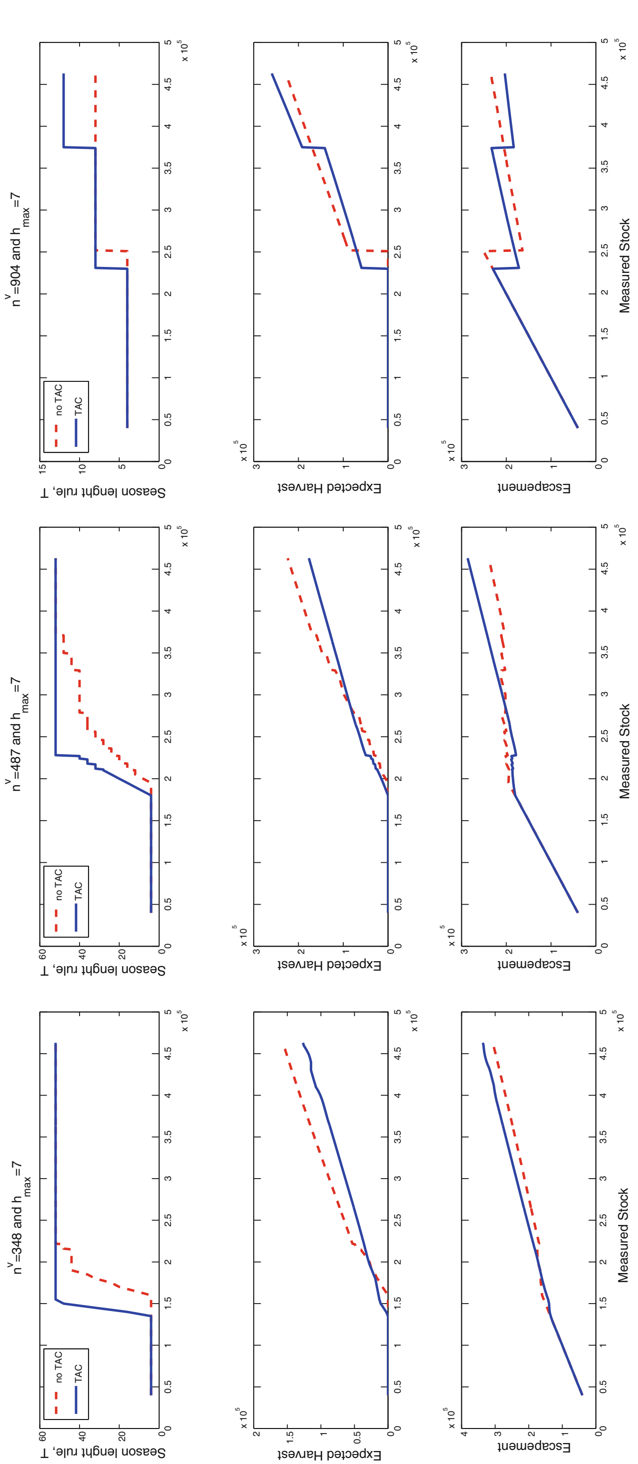


**Fig. 7** Model with uncertain stock. Optimal harvests, escapement and length seasons as functions of stock. **a** Small number of vessels, **b** medium number of vessels, **c** large number of vessels

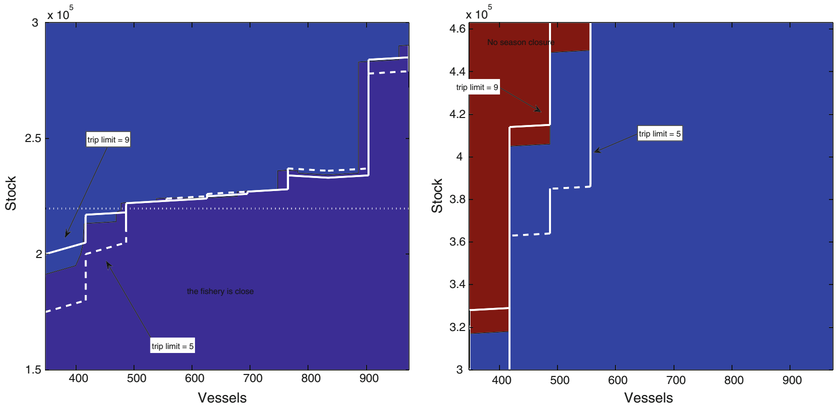


**Fig. 8** Effects of changes in the trip limit parameter

## 5.2 Properties of Each Management Regime

Once the optimal season lengths are obtained, the effect of each regimen in biological terms (stock and escapement) and economic (profits and welfare) terms can be compared. To that end the optimal season length for the fishery is simulated 100 times for each regulatory body. As there is a risk of extinction under uncertainty, each simulation is run over 1,000 seasons.

To analyse the implications of different fleet sizes on policy variables, the experiment is run for fisheries with different numbers of licences.[18] We start with 348 licences, which is the minimum number which would generate aggregate captures compatible with the captures observed for the Iberian sardine fishery. Then we run the simulations increasing the number of licences by 20, 40 and so on up to 180%.

In all the implementations, the initial measured stock is taken to be that of the constant escapement policy level in a deterministic set up ($G(S^*) = 357{,}743$ Tn). Since there is a risk of extinction under uncertainty, we run each simulation for a long period (1,000 seasons). Like Sethi et al. (2005), we use a discount factor of 0.95 to discount the future profits. We summarised the results calculating the average and the coefficient of variation (cv) for: (i) the policy instruments (season length and target quotas); (ii) the real stock and escapement and; (iii) the economic results: harvest, yearly profits and net present value of welfare, which is equal to the product of the number of vessels multiplied by the net present value of individual profits. These average values can be considered as the mean of the stationary distribution of the fishery.

Table 4 and Fig. 9 show the averages of the relevant variables for the 100 simulations run for the two regulatory bodies and considering 10 different numbers of licences. Red lines show regulatory body I (without TAC). Blue lines show regulatory body II (with TAC). The figure reveals some significant findings. First, the larger the number of vessels, the lower the season length, escapement, harvest, individual profits and welfare are, regardless of the regulatory body. Second, the empirical simulations show that the use of TACs along with fishing periods may improve the economic variables depending on the size of the fleet. In particular, when the number of licences is small the introduction of TACs reduces harvest,

[18] The experiment has been also run for different trip limit values. However, the results are qualitatively similar for all the values. We have therefore decided to show only the results for the benchmark parameter, $\overline{h} = 7$ in the main text. Figure 12 and Table 7 in the Appendix show in detail the results for all the cases analysed.

**Table 4** Means ($\bar{h} = 7$)

| Vessels | 348 | 417 | 487 | 556 | 626 | 695 | 765 | 834 | 904 | 974 |
|---|---|---|---|---|---|---|---|---|---|---|
| *T season* | | | | | | | | | | |
| Without TAC | 364.00 | 364.00 | 290.61 | 251.54 | 167.84 | 154.27 | 85.95 | 79.12 | 50.39 | 48.45 |
| With TAC | 364.00 | 364.00 | 364.00 | 364.00 | 347.11 | 324.87 | 162.56 | 148.46 | 71.36 | 64.79 |
| *Quota* | | | | | | | | | | |
| Without TAC | 129.17 | 131.95 | 112.69 | 104.08 | 98.69 | 98.91 | 100.56 | 97.90 | 107.80 | 105.70 |
| With TAC | 142.93 | 160.25 | 188.50 | 192.01 | 184.35 | 184.71 | 185.99 | 185.19 | 179.51 | 183.78 |
| *Stock* | | | | | | | | | | |
| Without TAC | 396.41 | 364.51 | 318.96 | 310.43 | 300.54 | 300.45 | 299.03 | 297.04 | 303.10 | 298.02 |
| With TAC | 430.19 | 423.41 | 405.98 | 402.35 | 395.55 | 395.33 | 393.88 | 394.68 | 390.13 | 384.41 |
| *Escapement* | | | | | | | | | | |
| Without TAC | 261.48 | 225.35 | 187.22 | 181.42 | 175.40 | 175.31 | 174.43 | 173.32 | 175.65 | 172.73 |
| With TAC | 330.51 | 312.68 | 279.38 | 273.60 | 266.27 | 265.97 | 264.01 | 265.32 | 260.99 | 253.43 |
| *Harvest* | | | | | | | | | | |
| Without TAC | 134.94 | 139.15 | 131.74 | 129.01 | 125.14 | 125.14 | 124.60 | 123.72 | 127.45 | 125.29 |
| With TAC | 99.68 | 110.73 | 126.60 | 128.75 | 129.28 | 129.36 | 129.87 | 129.36 | 129.14 | 130.98 |
| *Profits* | | | | | | | | | | |
| Without TAC | 17.34 | 15.18 | 10.47 | 9.01 | 4.97 | 4.47 | 1.98 | 1.80 | 0.65 | 0.57 |
| With TAC | 16.02 | 15.13 | 12.49 | 11.11 | 6.21 | 5.59 | 2.54 | 2.32 | 0.85 | 0.80 |

**Table 4** Continued

| Vessels | 348 | 417 | 487 | 556 | 626 | 695 | 765 | 834 | 904 | 974 |
|---|---|---|---|---|---|---|---|---|---|---|
| *Net present value of profits* | | | | | | | | | | |
| Without TAC | 327.39 | 288.74 | 202.70 | 175.07 | 97.13 | 87.43 | 38.98 | 35.22 | 12.86 | 11.39 |
| With TAC | 303.33 | 285.94 | 235.77 | 209.32 | 116.55 | 105.00 | 47.98 | 43.72 | 16.15 | 15.08 |
| *Net present value of welfare* | | | | | | | | | | |
| With TAC | 113,829 | 120,468 | 98,667 | 97,390 | 60,788 | 60,794 | 29,816 | 29,390 | 11,628 | 11,093 |
| With TAC | 105,461 | 119,302 | 114,764 | 116,444 | 72,941 | 73,016 | 36,698 | 36,481 | 14,600 | 14,680 |

Units: T Season (days); escapement, harvest, profits, net present value of profits and net present value of welfare (Tn)
Results: Average from 100 simulations of 1,000 periods

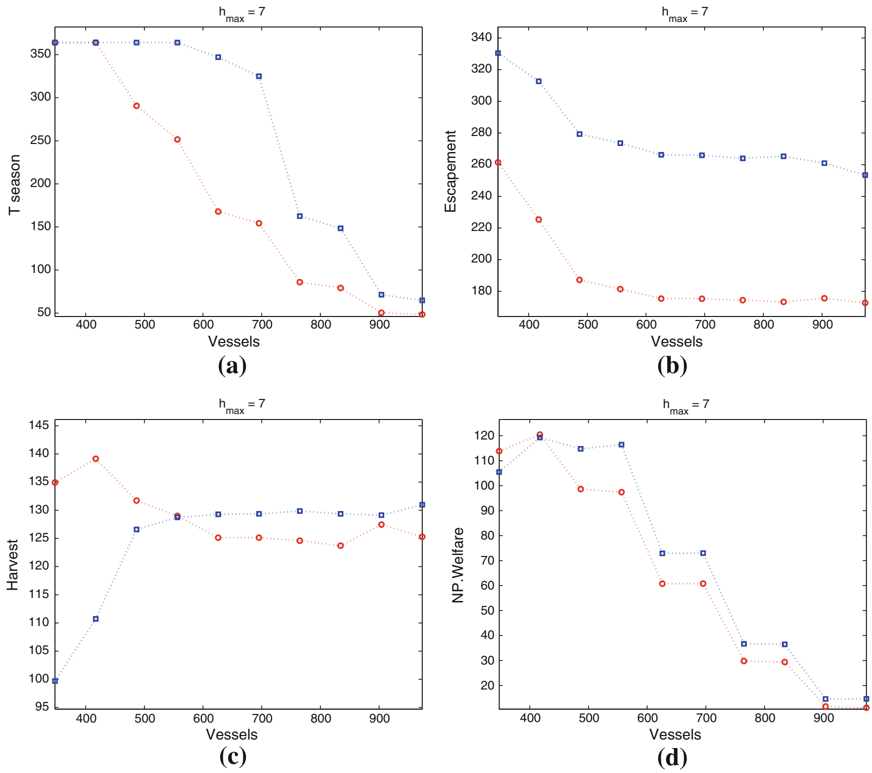


**Fig. 9** Main variables under the regulatory bodies I (no TAC, red line) and II (TAC, blue line). **a** Season length. **b** Escapement. **c** Harvest. **d** Welfare. (Color figure online)

profits and welfare. However, when the fleet is large using TACs along with fishing periods leads to increases in both biological and economic variables.

Finally Table 5 shows the coefficient of variation (cv) associated with the 100 simulations run for the two regulatory bodies, considering 10 different numbers of licences. Two empirical facts stand out from the results. First, the use of TACs along with fishing periods reduces the variability of all the variables simulated for medium and large number of licences. Second, the cv is more sensitive to changes in the number of licences when TACs are not used than when they are used. For instance, without TACs the harvest cv ranges from 0.60 to 1.01 depending on the number of licences. However, with TACs the harvest cv ranges from 0.50 to 0.55.

Note that in our model, unlike Danielsson (2002), the relative size of uncertainty (variance) is an endogenous variable induced by the regulatory regime. The larger the number of vessels, the greater the variability in the catch-effort relationship relative to stock recruitment is, and therefore the greater the comparative advantage of combining harvest controls (TACs) with effort controls (fishing periods) is.

## 5.3 Fleet Size

As can be seen in Table 4, the size of the fleet is a relevant variable that affects the results. In particular, it can be seen that maximum welfare is reached when the fleet is medium sized. In fact, if the regulator could select the number of licences both would choose to issue 417.

**Table 5** Coefficients of variation ($\overline{h} = 7$)

| Vessels | 348 | 417 | 487 | 556 | 626 | 695 | 765 | 834 | 904 | 974 |
|---|---|---|---|---|---|---|---|---|---|---|
| *T season* | | | | | | | | | | |
| Without TAC | 0.00 | 0.00 | 0.16 | 0.27 | 0.39 | 0.38 | 0.33 | 0.33 | 0.22 | 0.26 |
| With TAC | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.09 | 0.12 | 0.10 | 0.19 | 0.20 |
| *Quota* | | | | | | | | | | |
| Without TAC | 0.07 | 0.03 | 0.34 | 0.45 | 0.53 | 0.53 | 0.55 | 0.56 | 0.54 | 0.64 |
| With TAC | 0.08 | 0.09 | 0.10 | 0.14 | 0.18 | 0.18 | 0.19 | 0.16 | 0.14 | 0.15 |
| *Stock* | | | | | | | | | | |
| Without TAC | 0.26 | 0.26 | 0.29 | 0.31 | 0.34 | 0.34 | 0.35 | 0.36 | 0.31 | 0.33 |
| With TAC | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.28 | 0.28 |
| *Escapement* | | | | | | | | | | |
| Without TAC | 0.10 | 0.03 | 0.17 | 0.21 | 0.27 | 0.27 | 0.28 | 0.29 | 0.22 | 0.26 |
| With TAC | 0.21 | 0.20 | 0.18 | 0.17 | 0.19 | 0.19 | 0.19 | 0.19 | 0.21 | 0.20 |
| *Harvest* | | | | | | | | | | |
| Without TAC | 0.60 | 0.66 | 0.86 | 0.94 | 1.04 | 1.04 | 1.05 | 1.06 | 0.92 | 1.01 |
| With TAC | 0.50 | 0.51 | 0.56 | 0.57 | 0.57 | 0.57 | 0.57 | 0.56 | 0.52 | 0.55 |
| *Profits* | | | | | | | | | | |
| Without TAC | 0.53 | 0.60 | 0.82 | 0.89 | 1.02 | 1.02 | 1.06 | 1.08 | 1.13 | 1.30 |
| With TAC | 0.42 | 0.44 | 0.53 | 0.56 | 0.60 | 0.60 | 0.61 | 0.60 | 0.62 | 0.66 |

100 simulations of 1,000 periods

**Table 6** Welfare and the size of the fleet

| Vessels | 348 | 417 | 487 | 556 | 626 | 695 | 765 | 834 | 904 | 974 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\overline{h} = 5$ | | | | | | | | | | |
| Without TAC | 95.49 | **105.30** | 95.34 | 96.26 | 57.71 | 57.65 | 28.20 | 28.15 | 9.99 | 9.82 |
| With TAC | 87.58 | 98.32 | 96.12 | **99.89** | 68.64 | 68.71 | 34.15 | 34.44 | 13.41 | 13.48 |
| $\overline{h} = 7$ | | | | | | | | | | |
| Without TAC | 113.82 | **120.47** | 98.67 | 97.39 | 60.79 | 60.79 | 29.82 | 29.39 | 11.63 | 11.09 |
| With TAC | 105.46 | **119.30** | 114.76 | 116.44 | 72.94 | 73.02 | 36.70 | 36.48 | 14.60 | 14.68 |
| $\overline{h} = 9$ | | | | | | | | | | |
| Without TAC | 122.66 | **125.50** | 100.97 | 99.38 | 61.94 | 61.87 | 30.24 | 30.19 | 11.63 | 11.10 |
| With TAC | 114.66 | **127.84** | 121.05 | 122.33 | 75.01 | 75.14 | 37.59 | 37.45 | 15.14 | 15.24 |

100 simulations of 1,000 periods

It is worth mentioning that in both cases the optimal season length implies that the fishery is open all year around.

These results do not change qualitatively when the trip limit is changed. Table 6 summarises the welfare of the fisheries for the two regulatory bodies assuming three different trip limits ($\overline{h} = 5, \overline{h} = 7, \overline{h} = 9$). The maximum welfare under each scenario studied is marked in bold. Note that the minimum fleet size ($n^v = 348$) is never that which leads to the maximum welfare, as the fleet size may be too small to capture the entire available harvest. On the other hand, whenever the number of licences implies maximum welfare, not restricting access to the fishery is optimal (see Table 7 in the Appendix). In the light of these results, it

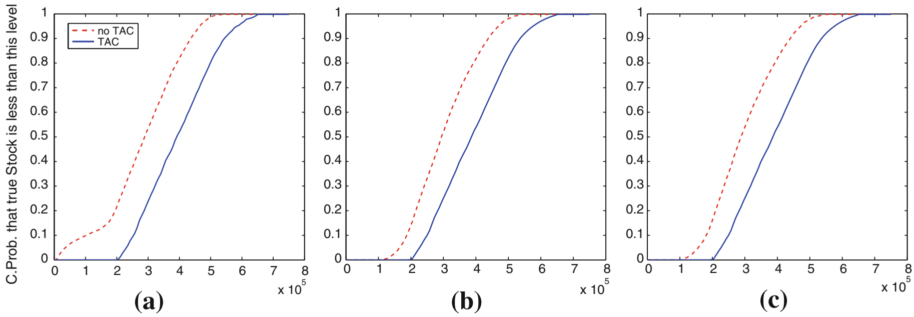


**Fig. 10** CDF of measured stock under uncertainty. **a** $\overline{h} = 5$. **b** $\overline{h} = 7$. **c** $\overline{h} = 9$

can be concluded that the regulator would rather select the number of licences than restrict the season length. Nevertheless, from the management point of view, it would be very hard to implement a policy where the number of licences varies from year to year. Furthermore such a policy would have major implication for incentives to invest if investment and disinvestment do not occur at the same capital price.

## 5.4 Extinction

In an endogenous model the risk of extinction is never associated with low levels of stock. When that happens, vessels do not find it profitable to fish and decide not to operate. Moreover, when the stock is low enough, the regulator finds it optimal to close the fishery.

By contrast, the risk of extinction may show up when the fishery is characterised by a combination of high stocks and large number of licences. This risk actually appears when large measurement stocks lead vessels to fish for more days and to harvest more per day. If the fishery is regulated only via fishing periods the fleet may find it profitable to harvest too much in a short period of time and the stock may disappear if the number of vessels is high enough. This negative effect does not appear when the number of vessels is small because individual fishing capacity may constrain aggregate catches, thus preventing total resource depletion.

When the fishery is regulated using TAC along with fishing periods, the extinction risk disappears even for large numbers of licences as the fishery is closed once the quota is exhausted and the stock is thus not depleted.[19] It can therefore be said that the introduction of TACs as a management instrument prevents the risk of extinction.

Figure 10 illustrates the relationship between measured stock and the cumulative probability of the *ex post* stock being below that level. This cumulative probability is calculated as the proportion of simulations in which this happens at some time during all the simulations run. Red lines illustrate the relationship under regulatory body I (without TAC). Blue lines show it under the regulatory body II (with TAC). Thehe following results stand out: (i) when the measured stock is low, the probability of the measured stock in the next period being below the current measured stock is near zero regardless of which regulatory body is considered; (ii) When the measured stock is high enough the probability of the measured stock in the next period being below the current expected stock is always higher when TACs are not used as a management instrument. Therefore it can be concluded that the introduction of TACs as a management instrument reduces the risk of extinction for high measured stocks.

[19] Note that the quota is optimally set by managers consistently with the season length announced, the trip limit, the industry investment decisions and the previous stock (see constraints in the manager's optimisation problem (13)).

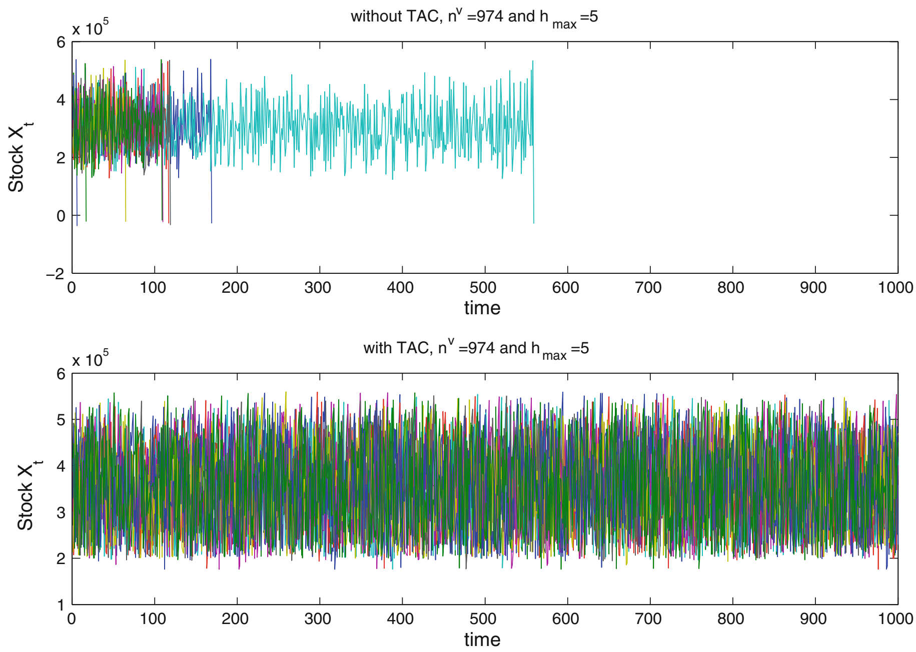


**Fig. 11** Risk of extinction for large fleets

These results can be also appreciated in Fig. 11. This figure illustrates the changes over time in the stock over the 1,000 periods simulated under regulatory body I (without TAC, top panel) and under regulatory body II (with TAC, bottom panel) for the case of a large fleet. Each colour indicates a different simulation. It can be seen that without TACs the stock level drops to zero in many simulations and extinction occurs. However, with TAC this never happens.

## 6 Conclusions

We develop an endogenous regulated restricted-access fishery management model with multiple inputs that builds on Homans and Wilen (1997) and Anderson (2000). We assume that the fishery manager can simultaneously use daily quotas (or trip limits), fishing periods (the overall limits on the fishing season) and total allowed quotas to meet the target harvest. As in Clark and Kirkwood (1986), we assume that when the fishery manager sets quotas he does not know the real state of the stock. Following Arnason (2000), we solve the fishery management problem numerically taking into account that the behaviour of individual agents is generated by endogenous optimization.

This endogenous optimization problem is applied to the Iberian sardine stock. Simulations show significant conclusions.

We find that higher levels of uncertainty regarding the state of the stock reduce the likelihood of the fishery being closed. Therefore, our result is along the same lines that of Sethi et al. (2005).

We ask in the title why fishery agencies use TACs along with fishing periods: we show that the use of TACs as a management instrument in fisheries already regulated with fishing periods leads to longer optimal season lengths and larger harvests, especially for medium and high numbers of licences. However, this effect on economic variables depends on the size of the fleet. In particular, when the number of licences is small the introduction of TACs reduces harvest, profits and welfare. However, when the fleet is large using TACs increases all biological and economic variables.

Moreover, the introduction of TACs as a management instrument reduces the risk of extinction. The risk of extinction appears in our model whenever the fishery is characterised by a combination of high stocks and large numbers of licences. Large measurement stocks lead vessels to fish for more days and to harvest more per day. If the fishery is regulated only with fishing periods, the fleet may find it profitable to harvest too much in a short period of time and the stock may disappear if the number of vessels is high enough. However, when the fishery is regulated using TAC along with fishing periods the extinction risk disappears because the fishery is closed once the quota is exhausted and the stock is thus not depleted. On the other hand in a context where strategic effects in the race to fish are incorporated this result would have probably been even stronger.

Nevertheless, it must be said that our results are limited by the assumptions of the model used. In particular, the following may be relevant. First, individual vessels adjust their capacity (horsepower, length, etc) only between seasons based on their anticipation of the stock level and regulation. If the regulator does not consider fishing periods and the expected stock is high, individual vessels will increase their capacity to harvest too much in a short period of time. Second, fishing opportunities are modelled assuming that there is a luck component which is i.i.d. variable. So past errors in measured stock are not considered by fishermen. Third, vessels are considered to be identical, so in equilibrium they all take the same decision on whether or not to exit the fishery. Fourth, when the regulator considers quotas as a management instrument along with fishing periods, those quotas are not selected optimally from the point of view of the fishery.

Focusing on welfare we find that from the point of view of the regulator it would be better to select the number of licences and not to restrict the season length. Therefore an interesting issue to be analysed in future research is how this optimal number of licenses is arrived at given the initial situation of the fleet. In fact some studies suggest that there is excess capacity in many stocks (Lazkano 2008). Moreover, given that technical change exacerbates excess fishing capacity and low returns to fishing effort and investment (see Kirkley et al. 2004), the optimal number of licensees is an endogenous variable that depends on the rate of growth of technical change.

Another interesting point is that our analysis is based on quotas which are endogenously selected to be compatible with the expected harvest given a season length. However, it may be that this quota does not coincide with the optimal quota from the viewpoint of the fishery authorities. It would therefore be interesting for future research to analysed how optimal quotas can be implemented if they are not consistent (and therefore credible) with the expected harvests given the season length announced.

Other interesting regulation questions to be addressed include the role of mesh size regulations and how TAC shoulde be share between different gears. Diekert et al. (2010) suggest that some commercial fisheries are wasting a large part of their potential due to the use of small mesh size rather than excessive effort. Our model could be extended by introducing more realistic age-structured resource dynamics, as in Tahvonen (2009) and Bjørndal et al. (2004a,b), to study the effects of changes in mesh sizes using the methods developed in Da Rocha et al. (2010) and Da Rocha and Gutiérrez (2011).

## Appendix

See Fig. 12 and Table 7.

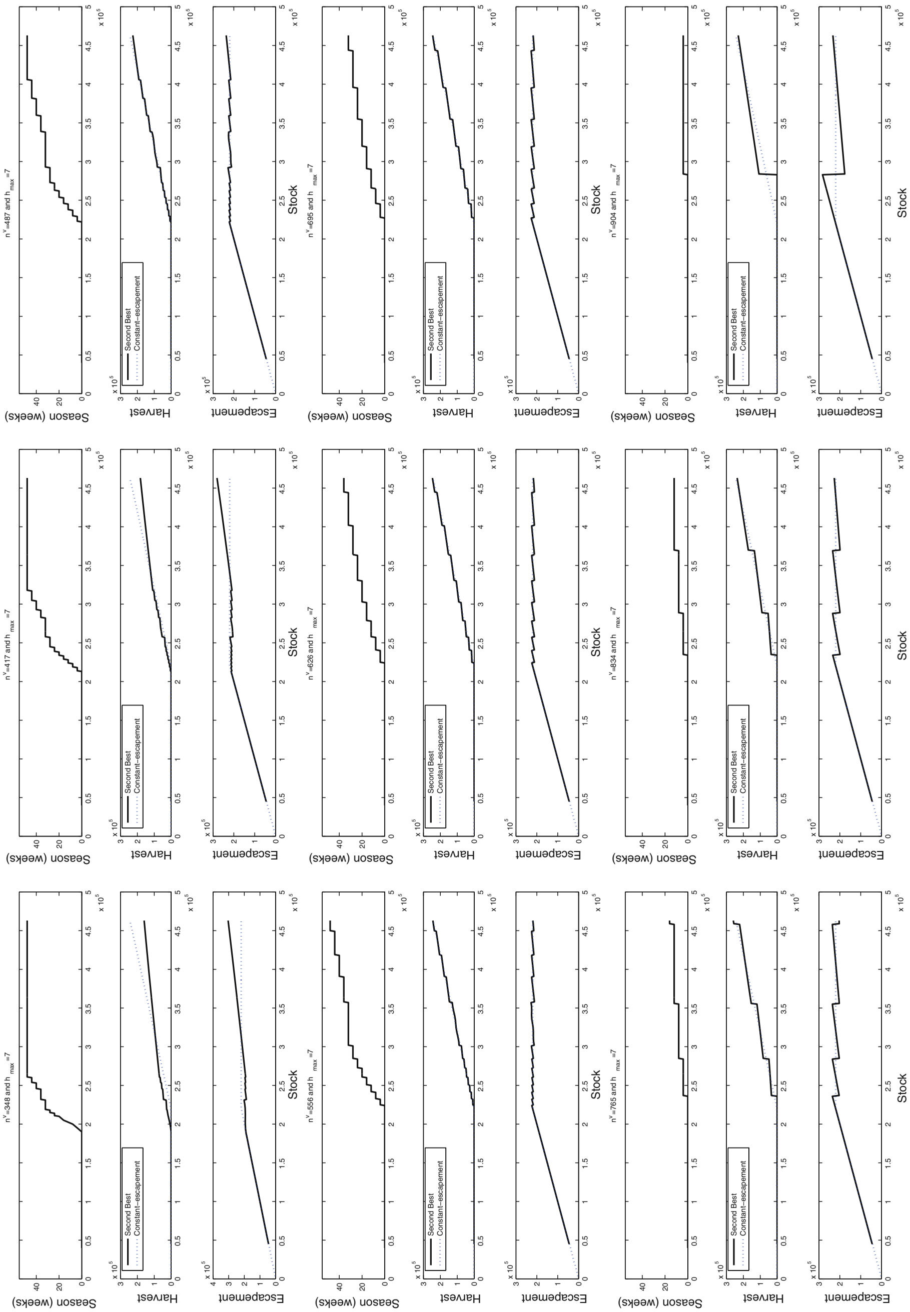


**Fig. 12** Slides of the $T(X_{t,1}, n^v | \overline{h} = 7)$ rule for different number of vessels

**Table 7** Experiments

| *n* vessels<br>TAC | 347.68<br>0 | 347.68<br>1 | 417.22<br>0 | 417.22<br>1 | 486.76<br>0 | 486.76<br>1 | 556.29<br>0 | 556.29<br>1 | 625.83<br>0 | 625.83<br>1 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\overline{h} = 5$ | | | | | | | | | | |
| T season | 364.00 | 364.00 | 364.00 | 364.00 | 363.86 | 364.00 | 350.11 | 364.00 | 179.84 | 357.74 |
| c.v. | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.07 | 0.00 | 0.39 | 0.04 |
| Quota | 123.61 | 129.58 | 131.19 | 142.76 | 132.67 | 166.90 | 125.65 | 171.25 | 99.15 | 184.11 |
| c.v. | 0.08 | 0.07 | 0.06 | 0.07 | 0.06 | 0.10 | 0.17 | 0.11 | 0.53 | 0.19 |
| Stock | 414.39 | 432.58 | 393.67 | 426.94 | 346.10 | 411.33 | 333.72 | 405.07 | 301.03 | 393.96 |
| c.v. | 0.27 | 0.26 | 0.26 | 0.27 | 0.26 | 0.27 | 0.27 | 0.27 | 0.34 | 0.27 |
| Escapement | 290.42 | 341.09 | 259.17 | 325.24 | 208.56 | 292.31 | 198.40 | 282.28 | 175.29 | 264.60 |
| c.v. | 0.16 | 0.22 | 0.12 | 0.22 | 0.06 | 0.21 | 0.11 | 0.21 | 0.26 | 0.19 |
| Harvest | 123.97 | 91.49 | 134.50 | 101.69 | 137.53 | 119.02 | 135.32 | 122.78 | 125.74 | 129.36 |
| c.v. | 0.54 | 0.48 | 0.57 | 0.47 | 0.71 | 0.49 | 0.76 | 0.50 | 1.02 | 0.56 |
| Profits | 14.55 | 13.32 | 13.39 | 12.45 | 10.22 | 10.45 | 8.98 | 9.49 | 4.72 | 5.80 |
| c.v. | 0.45 | 0.37 | 0.48 | 0.37 | 0.63 | 0.45 | 0.70 | 0.48 | 0.98 | 0.57 |
| NP. Profits | 274.65 | 251.90 | 253.41 | 235.65 | 195.86 | 197.47 | 173.04 | 179.56 | 92.22 | 109.67 |
| NP. Welfare | 95.49 | 87.58 | 105.73 | 98.32 | 95.34 | 96.12 | 96.26 | 99.89 | 57.71 | 68.64 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $\overline{h} = 7$ | | | | | | | | | | |
| T season | 364.00 | 364.00 | 364.00 | 364.00 | 290.44 | 364.00 | 251.56 | 364.00 | 167.30 | 346.93 |
| c.v. | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.00 | 0.27 | 0.00 | 0.39 | 0.06 |
| Quota | 129.13 | 142.92 | 131.95 | 160.24 | 112.55 | 188.43 | 103.86 | 191.92 | 98.12 | 184.12 |
| c.v. | 0.07 | 0.08 | 0.03 | 0.09 | 0.34 | 0.10 | 0.45 | 0.14 | 0.54 | 0.18 |
| Stock | 396.10 | 429.88 | 364.31 | 423.08 | 318.77 | 405.51 | 310.27 | 401.86 | 300.16 | 394.98 |
| c.v. | 0.26 | 0.26 | 0.26 | 0.27 | 0.29 | 0.27 | 0.31 | 0.27 | 0.34 | 0.27 |
| Escapement | 261.36 | 330.20 | 225.35 | 312.40 | 187.13 | 279.03 | 181.26 | 273.26 | 174.94 | 265.90 |
| c.v. | 0.10 | 0.21 | 0.03 | 0.20 | 0.17 | 0.17 | 0.21 | 0.17 | 0.27 | 0.19 |
| Harvest | 134.75 | 99.68 | 138.96 | 110.68 | 131.64 | 126.48 | 129.00 | 128.59 | 125.22 | 129.09 |
| c.v. | 0.60 | 0.50 | 0.65 | 0.51 | 0.86 | 0.55 | 0.94 | 0.57 | 1.04 | 0.56 |
| Profits | 17.32 | 16.02 | 15.16 | 15.12 | 10.46 | 12.49 | 9.01 | 11.10 | 4.97 | 6.19 |
| c.v. | 0.53 | 0.42 | 0.60 | 0.44 | 0.82 | 0.53 | 0.89 | 0.56 | 1.01 | 0.59 |
| NP. Profits | 327.52 | 302.66 | 288.63 | 285.45 | 202.67 | 235.57 | 175.08 | 209.28 | 97.16 | 116.79 |
| NP. Welfare | 113.87 | 105.23 | 120.42 | 119.10 | 98.65 | 114.66 | 97.40 | 116.42 | 60.80 | 73.09 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $\overline{h} = 9$ | | | | | | | | | | |
| T season | 364.00 | 364.00 | 364.00 | 364.00 | 268.97 | 364.00 | 231.68 | 364.00 | 163.60 | 343.56 |
| c.v. | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 0.32 | 0.00 | 0.40 | 0.06 |
| Quota | 128.71 | 148.22 | 129.43 | 165.07 | 107.97 | 191.20 | 101.39 | 193.65 | 97.97 | 184.41 |
| c.v. | 0.05 | 0.09 | 0.05 | 0.09 | 0.41 | 0.12 | 0.50 | 0.14 | 0.54 | 0.19 |
| Stock | 383.93 | 427.05 | 352.22 | 420.30 | 314.28 | 405.38 | 307.10 | 402.49 | 299.36 | 395.66 |
| c.v. | 0.26 | 0.27 | 0.26 | 0.27 | 0.30 | 0.27 | 0.32 | 0.27 | 0.35 | 0.27 |
| Escapement | 246.18 | 322.86 | 214.08 | 306.21 | 184.07 | 278.22 | 179.44 | 273.78 | 174.51 | 266.68 |
| c.v. | 0.06 | 0.21 | 0.05 | 0.20 | 0.20 | 0.17 | 0.24 | 0.16 | 0.28 | 0.19 |
| Harvest | 137.75 | 104.18 | 138.14 | 114.10 | 130.22 | 127.15 | 127.66 | 128.71 | 124.84 | 128.98 |

**Table 7** Continued

| *n* vessels<br>TAC | 347.68<br>0 | 347.68<br>1 | 417.22<br>0 | 417.22<br>1 | 486.76<br>0 | 486.76<br>1 | 556.29<br>0 | 556.29<br>1 | 625.83<br>0 | 625.83<br>1 |
|---|---|---|---|---|---|---|---|---|---|---|
| c.v. | 0.64 | 0.50 | 0.70 | 0.52 | 0.91 | 0.57 | 0.99 | 0.58 | 1.05 | 0.57 |
| Profits | 18.64 | 17.49 | 15.75 | 16.26 | 10.69 | 13.21 | 9.18 | 11.68 | 5.07 | 6.36 |
| c.v. | 0.59 | 0.46 | 0.67 | 0.48 | 0.88 | 0.56 | 0.96 | 0.58 | 1.03 | 0.61 |
| NP. Profits | 352.80 | 329.77 | 300.80 | 306.42 | 207.43 | 248.68 | 178.65 | 219.90 | 98.97 | 119.86 |
| NP. Welfare | 122.66 | 114.66 | 125.50 | 127.84 | 100.97 | 121.05 | 99.38 | 122.33 | 61.94 | 75.01 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| *n* vessels<br>TAC | 695.37<br>0 | 695.37<br>1 | 764.90<br>0 | 764.90<br>1 | 834.44<br>0 | 834.44<br>1 | 903.98<br>0 | 903.98<br>1 | 973.51<br>0 | 973.51<br>1 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\overline{h} = 5$ | | | | | | | | | | |
| T season | 164.72 | 337.95 | 88.97 | 171.04 | 85.35 | 156.76 | 50.32 | 79.22 | 7.52 | 70.43 |
| c.v. | 0.38 | 0.07 | 0.33 | 0.11 | 0.33 | 0.13 | 0.25 | 0.13 | 3.99 | 0.20 |
| Quota | 99.30 | 184.15 | 98.64 | 183.10 | 100.74 | 185.89 | 104.83 | 172.87 | 16.64 | 177.80 |
| c.v. | 0.52 | 0.19 | 0.54 | 0.20 | 0.54 | 0.19 | 0.50 | 0.13 | 4.33 | 0.14 |
| Stock | 301.11 | 393.93 | 299.23 | 393.61 | 300.16 | 391.63 | 283.18 | 395.37 | 44.40 | 389.39 |
| c.v. | 0.34 | 0.27 | 0.34 | 0.27 | 0.34 | 0.27 | 0.42 | 0.27 | 4.11 | 0.28 |
| Escapement | 175.36 | 264.57 | 174.10 | 264.43 | 174.68 | 261.55 | 164.36 | 269.21 | 25.62 | 260.75 |
| c.v. | 0.26 | 0.19 | 0.27 | 0.19 | 0.27 | 0.19 | 0.36 | 0.22 | 4.12 | 0.21 |
| Harvest | 125.75 | 129.36 | 125.13 | 129.19 | 125.48 | 130.08 | 118.82 | 126.16 | 18.79 | 128.63 |
| c.v. | 1.02 | 0.57 | 1.03 | 0.57 | 1.03 | 0.57 | 1.03 | 0.50 | 5.49 | 0.52 |
| Profits | 4.24 | 5.23 | 1.88 | 2.36 | 1.72 | 2.18 | 0.55 | 0.79 | 0.08 | 0.73 |
| c.v. | 0.98 | 0.57 | 1.02 | 0.58 | 1.03 | 0.58 | 1.28 | 0.57 | 6.08 | 0.62 |
| NP. Profits | 82.91 | 98.81 | 36.87 | 44.65 | 33.73 | 41.27 | 11.05 | 14.83 | 10.09 | 13.84 |
| NP. Welfare | 57.65 | 68.71 | 28.20 | 34.15 | 28.15 | 34.44 | 9.99 | 13.41 | 9.82 | 13.48 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| $\overline{h} = 7$ | | | | | | | | | | |
| T season | 153.54 | 324.79 | 85.53 | 162.50 | 78.93 | 148.37 | 48.22 | 71.43 | 48.39 | 64.79 |
| c.v. | 0.38 | 0.09 | 0.34 | 0.12 | 0.33 | 0.10 | 0.32 | 0.19 | 0.26 | 0.20 |
| Quota | 98.15 | 184.46 | 99.68 | 185.79 | 97.41 | 184.90 | 103.28 | 179.36 | 105.17 | 183.65 |
| c.v. | 0.53 | 0.18 | 0.56 | 0.19 | 0.57 | 0.16 | 0.62 | 0.14 | 0.64 | 0.15 |
| Stock | 299.94 | 394.78 | 298.55 | 393.34 | 297.03 | 394.03 | 289.55 | 389.59 | 297.56 | 383.87 |
| c.v. | 0.34 | 0.27 | 0.35 | 0.27 | 0.36 | 0.27 | 0.40 | 0.28 | 0.33 | 0.28 |
| Escapement | 174.73 | 265.59 | 173.86 | 263.67 | 173.04 | 264.88 | 167.77 | 260.58 | 172.40 | 253.07 |
| c.v. | 0.27 | 0.19 | 0.28 | 0.19 | 0.29 | 0.19 | 0.32 | 0.21 | 0.26 | 0.20 |
| Harvest | 125.22 | 129.19 | 124.69 | 129.67 | 123.99 | 129.15 | 121.78 | 129.01 | 125.16 | 130.81 |
| c.v. | 1.04 | 0.57 | 1.05 | 0.57 | 1.05 | 0.56 | 1.02 | 0.52 | 1.00 | 0.55 |
| Profits | 4.47 | 5.58 | 1.99 | 2.54 | 1.80 | 2.31 | 0.62 | 0.85 | 0.57 | 0.79 |
| c.v. | 1.01 | 0.59 | 1.06 | 0.60 | 1.08 | 0.60 | 1.24 | 0.62 | 1.30 | 0.67 |
| NP. Profits | 87.43 | 105.17 | 38.88 | 47.93 | 35.29 | 43.68 | 12.79 | 16.10 | 11.34 | 15.06 |
| NP. Welfare | 60.80 | 73.13 | 29.74 | 36.66 | 29.45 | 36.45 | 11.56 | 14.55 | 11.04 | 14.66 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.08 | 0.00 | 0.00 | 0.00 |
| $\overline{h} = 9$ | | | | | | | | | | |
| T season | 147.36 | 320.87 | 83.22 | 157.96 | 77.02 | 147.28 | 49.54 | 68.63 | 47.49 | 63.56 |
| c.v. | 0.39 | 0.10 | 0.34 | 0.12 | 0.32 | 0.10 | 0.24 | 0.20 | 0.27 | 0.20 |

**Table 7** Continued

| *n* vessels<br>TAC | 695.37<br>0 | 695.37<br>1 | 764.90<br>0 | 764.90<br>1 | 834.44<br>0 | 834.44<br>1 | 903.98<br>0 | 903.98<br>1 | 973.51<br>0 | 973.51<br>1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Quota | 96.66 | 184.72 | 98.50 | 185.31 | 96.39 | 185.78 | 106.24 | 181.71 | 102.60 | 185.59 |
| c.v. | 0.55 | 0.19 | 0.57 | 0.18 | 0.56 | 0.18 | 0.58 | 0.15 | 0.69 | 0.15 |
| Stock | 299.06 | 395.37 | 296.75 | 394.23 | 296.67 | 393.88 | 299.33 | 387.52 | 292.52 | 381.74 |
| c.v. | 0.35 | 0.27 | 0.36 | 0.27 | 0.36 | 0.27 | 0.32 | 0.28 | 0.34 | 0.28 |
| Escapement | 174.30 | 266.26 | 172.86 | 264.93 | 172.76 | 264.47 | 173.39 | 257.62 | 169.11 | 250.27 |
| c.v. | 0.28 | 0.19 | 0.29 | 0.19 | 0.29 | 0.19 | 0.25 | 0.20 | 0.28 | 0.20 |
| Harvest | 124.75 | 129.11 | 123.89 | 129.30 | 123.92 | 129.41 | 125.94 | 129.90 | 123.40 | 131.48 |
| c.v. | 1.05 | 0.57 | 1.06 | 0.57 | 1.05 | 0.57 | 0.98 | 0.53 | 1.05 | 0.56 |
| Profits | 4.55 | 5.73 | 2.02 | 2.60 | 1.84 | 2.39 | 0.65 | 0.89 | 0.57 | 0.83 |
| c.v. | 1.04 | 0.61 | 1.08 | 0.61 | 1.08 | 0.61 | 1.22 | 0.65 | 1.37 | 0.69 |
| NP. Profits | 88.98 | 108.06 | 39.54 | 49.14 | 36.18 | 44.88 | 12.87 | 16.75 | 11.40 | 15.66 |
| NP. Welfare | 61.87 | 75.14 | 30.24 | 37.59 | 30.19 | 37.45 | 11.63 | 15.14 | 11.10 | 15.24 |
| Extinction | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

100 simulations of 1,000 periods

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