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Endogenous fisheries management in a stochastic model: Why do fishery agencies use TACs along with fishing periods?

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Abstract

The aim of this paper is to explain under which circumstances using TACs as instrument to manage a fishery along with fishing periods may be interesting from a regulatory point of view. In order to do this, the deterministic analysis of Homans and Wilen (1997) and Anderson (2000) is extended to a stochastic scenario where the resource cannot be measured accurately. The resulting endogenous stochastic model is numerically solved for finding the optimal control rules in the Iberian sardine stock. Three relevant conclusions can be highligted from simulations. First, the higher the uncertainty about the state of the stock is, the lower the probability of closing the fishery is. Second, the use of TACs as management instrument in fisheries already regulated with fishing periods leads to: i) An increase of the optimal season length and harvests, especially for medium and high number of licences, ii) An improvement of the biological and economic variables when the size of the fleet is large; and iii) Eliminate the extinction risk for the resource. And third, the regulator would rather select the number of licences and do not restrict the season length.

JEL Classification: Q22, Q28, Q57
Key word: fisheries management, TAC, season length, stock uncertainty

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1 Introduction

Since Homans and Wilen (1997) seminal paper, endogenous fisheries management literature considers that the regulatory process is divided into two stages. In the first stage, a target harvest quota is chosen to ensure the stock safety. In the second stage, managers choose one instrument to achieve the harvest target. Season length is the instrument analyzed by Homans and Wilen in his article. Anderson (2000) expands this analysis by incorporating disaggregated vessel behavior 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 simultaneously a mix of instruments: gear restrictions, minimum sizes, area closures, fishing periods (season length) and total allowed 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 the TAC of halibut to be taken during fishing periods for all areas (IPHC, 2009). Each area will be closed when the TAC is taken or the fishing period is over. In the same way, the European Commission also controls the number of fishing days together with other effort control measures since the year 2000 (see EC Regulation 43/2009).

The aim of this paper is to explain under which circumstances using TACs as instrument to manage a fishery along with fishing periods may be interesting from a regulatory point of view. For answering this question we extend the deterministic analysis of Homans and Wilen (1997) and Anderson (2000) to a stochastic scenario where the resource cannot be measured accurately (Clark and Kirkwood, 1986). In our model the regulatory process also is divided into two stages. In the first stage, a target harvest is chosen by the regulator. However, unlike Homans and Wilen (1997), we assume that fishery's 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 simultaneously used as instruments for achieving the target harvest.

Following Anderson (2000), we also include a disaggregated vessel analysis and intra-seasonal stock dynamics. We introduce a stochastic variable, the daily fishing opportunities or "luck", for reproducing the observed heterogeneity both in the daily harvest and the days per season at the vessel level. In particular, we consider that individual vessels choose each day, after observing the realization of the daily fishing opportunity, either to participate or not in the fishery. The participating vessel selects the daily use of its capacity. Vessels may change capacity between seasons based on expected net returns over the future season. Finally, we allow vessels to exit. Neither the fishery's 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 individual vessels decisions. 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 equal, on the specific combination of instruments chosen to implement the harvest target. In this sense, the model generates individual vessel behavior endogenously, as a function of the state variables and the policy instruments. Taking into consideration this optimal individual agents' behavior, 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 an endogenous stochastic optimization problem which can be computed numerically[1].

The model is used to compare the relative advantage of two different management regimes: Management regimes that combine season length and daily individual quotas; and Management regimes that combine season length, daily individual quotas and TACs. We found, that, by introducing uncertainty in a endogenous model we contribute to show that instruments that are equivalent in a determinist endogenous model reveal operational differences under uncertainty. TACs and fishing periods are not equivalent. In particular, in our model the "attempted" *ex-ante* harvest target and the true *ex-post* harvest implemented by using fishing periods will be different because both, the number of days each vessel decides to participate in the fishery and the intensity of use of the individual capacity, depend on the real state of the stock. The magnitude of this deviation, all else equal, is increasing in the stock size.

Therefore, combining TACs with fishing periods is not superfluous in uncertainty scenario. If the management regime introduces TACs, the *ex-post* harvest deviation will be truncated at a maximum. Regardless of the real state of the resource, harvest cannot be greater than the *ex-ante* harvest target because the fishery is closed when the TAC is taken (or the fishing period is over). We found that the combination of both 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.

[1]As Arnason (2000) points out endogenous optimization fisheries models can provide the necessary link between realistic fisheries management measures and the development of the fishery. Moreover, with the great progress in numerical computing speed, the practical use of this class of models has become feasible.

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

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

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

Why combining instruments is the best choice when uncertainty arises from inaccurate stock estimations? The answer already is in the fishery management under uncertainty literature. Reed (1979) found that when stock uncertainty comes from the stock recruitment relationship, the optimal policy is to allow a constant-escapement every period 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 extinction is possible. Sethi *et al.* (2005) compare both policies. They show that the main difference between constant-escapement and the (first best) optimal policy, is that, while constant-escapement calls for large catches when measured stock is large, the optimal policy, in order to avoid extinction, advocates higher escapement (lower catches) for large stock measurement. That is as Sethi *et al.* claims, *"due to the fact that both policies shut the fishery down at low stock size, one can never get extinction for low fish stock. However when stock size is large the potential measurement can be significantly larger and if the policy calls for large catches extinction, is more likely"*.

Our stochastic endogenous model can be seen as a framework that studies which instrument combinations allow for implementing optimal policy when *i)* stock uncertainty arises from inaccurate stock estimations and *ii)* uncertainty on the catch effort relationship is endogenously generated by the individual vessel behavior, as a function of the state variables and the policy instruments (a Ramsey problem).

When the number of licenses is given, 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 can be significantly larger and the optimal fishing periods rules call for longer seasons. Higher stocks also induce vessels both to participate 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, for fisheries with a large number of vessels, combining TACs with fishing periods calls for higher escapements and implement best policies.

The paper is organized as follows. In section 2 we build upon Homans and Wilen (1997) and Anderson (2000) an endogenous stochastic regulated restricted access fishery management model. The optimal feedback policy is characterized in section 3. Section 4 shows the strategy for solving numerically the model applied to the Iberian sardine stock. In Section 5 the results are illustrated. We conclude in Section 6.

2 A regulated restricted access fishery

We build upon Homans and Wilen (1997) and Anderson (2000) 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 its capacity (adjustments in horsepower, length and hold capacity) between seasons based upon the anticipation of both the biomass level and the regulations set by the agency. This capacity choice determines the daily fishing amount of individual effort (amount of labor, fuel, ..) and the number of days each vessel will be in the fishery. Therefore, for a given season length and a trip limit, we will show that daily fishing effort and the overall number of fishing days devoted to the fishery by each vessel is an endogenous variable that depends on the use or not of TACs along with fishing periods.

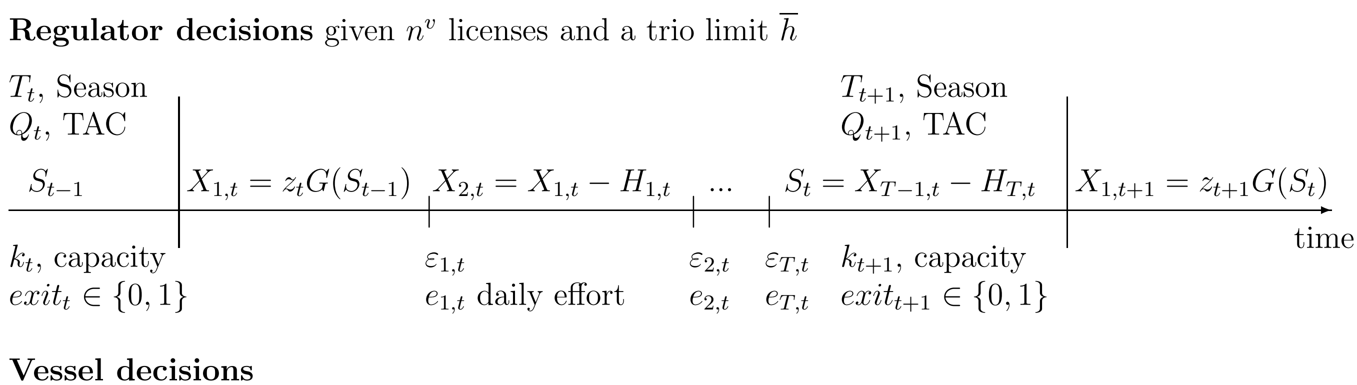
2.1 Industry behavior

As Anderson (2000) we use a discrete rather than a continuous model. Let us assume that the daily number of fish harvested by each vessel during season, t, is given by

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

where subscript d and t denotes day and season, respectively. θ 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 capacity, $X_{d,t}$ denotes the biomass, and $\xi_{d,t}$ is a stochastic variable that represents luck and/or fishing opportunities[2].

As in Homans and Wilen (1997), and Anderson (2000), individual vessels fishing capacity or power, k_t, is considered variable between seasons but fixed within a season. However, the daily use of this capacity depends on the stock size, $X_{d,t}$ and luck, $\xi_{d,t}$. After observing the daily fishing opportunity, each vessel decides if they operate or not and the daily effort, $e_{d,t}$. Moreover, between seasons, each vessel chooses its capacity for the next season and the regulator select the length season and the TAC, if it is the case, for the next season. Finally, we allow vessels to exist the fishery. Below we describe the information set available for each agent at any moment t.



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 cost of operation measured

[2] Vessels may know the daily fishing opportunity before the start of a fishing day analyzing objective variables such as altimetry and surface currents, sea surface and subsurface temperature, cloudless temperature, ocean color or location of ocean eddies and fronts. In fact, there are companies which offer fisherman satellite based services to support fishing.

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

in real terms.[4] The maximum daily net returns of an operating vessel is given by

$$\pi^o_{d,t} = \max_{e_{d,t}} \xi_{d,t}^{1-\gamma}\theta k^{\alpha} e^{\gamma}_{d,t} X_{d,t} - w e_{d,t},$$

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

where superscript ^{o} stands for operating vessel. From the first order conditions of this optimization problem, the daily effort function is obtained to be equal to

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

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

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

Note that, for each day, there exists an upper bound of the daily fishing opportunities, $\xi_{d,t} \geq \overline{\xi}_{d,t}$, for which the daily regulator's restriction affects the daily harvest. Formally, $\overline{\xi}_{d,t}$ satisfies $h_{d,t}(\overline{\xi}_{d,t}, k_t, X_{d,t}|\overline{h}) = \overline{h}$. Therefore,

$$\overline{\xi}_{d,t} = \frac{\overline{h}}{[\theta k^{\alpha}_t X_{d,t}(\gamma/w)^{\gamma}]^{1/(1-\gamma)}}. \tag{2}$$

Within season daily participation choice

We also assume that there is a daily fixed cost of operation equal to c_f, such that daily net returns are given by

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

This implies a lower bound of the daily fishing opportunities exists, $\xi_{d,t} \geq \underline{\xi}_{d,t}$, for which it is optimal not to participate (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

$$\underline{\xi}_{d,t} = \frac{[c_f/(1-\gamma)]}{[\theta k^{\alpha}_t X_{d,t}(\gamma/w)^{\gamma}]^{1/(1-\gamma)}}. \tag{3}$$

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

Within season stock dynamics and total harvest

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

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

where $f(\xi_{d,t})$ is the probability density function of the random variable $\xi_{d,t}$. Notice 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. Then, 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 stock dynamics intra season is given by

$$X_{d+1,t} = X_{d,t} - H_{d,t}(k_t, X_{d,t}|\overline{h}, n^v) \quad \forall d = 1, ..., T_t, \tag{4}$$

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

Notice that the shorter the season lenght is the higher the capacity that the vessel has to mantain to keep the same level of harvest.

Between seasons capacity choice

At the beginning of each season, each vessel selects the capacity that maximizes 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 profits for the season are equal to

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

Note that we allow vessels to adjust each season capacity as faster as they want (but inside the set $[\underline{k}, \overline{k}]$).

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

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

where $1-\phi$ is the labor share in the season net returns and p_k is the capital rental price.

The optimal investment rule of each vessel is determined by

$$\frac{\partial E_t\pi_t(k_t, X_{1,t}, T_t|\overline{h})}{\partial k_t} = p_k. \tag{5}$$

Under regular conditions we expect that shorter season lenghts leads vessels to select higher capacity to maximize the profits.

The industry welfare and exit decision

Note that the presence of seasonal fixed cost, $p_k\underline{k}$, implies that vessels can choose to exit the fishery if they expect a small probability of recovering the fixed cost. Formally, the optimal exit decision rule of each vessel is given by

$$exit(X_{1,t}, T_t|\overline{h}) = \begin{cases} 0 & \text{if } W(X_{1,t}|\overline{h}) > 0, \\ \\ 1 & \text{otherwise,} \end{cases} \tag{6}$$

where

$$W(X_{1,t}, T_t|\overline{h}) = E_t\pi(k_t, X_{1,t}, T_t)|\overline{h}) - p_k k_t + \beta W(X_{1,t+1}, T_{t+1}|\overline{h}).$$

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

2.2 Regulator behavior and between seasons stock dynamics

We assume that in each season, the growth of the stock 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,

$$X_{1,t} = z_t G(S_{t-1}). \tag{7}$$

The escapement S_{t-1}, is defined as

$$S_{t-1} = X_{1,t-1} - H_{t-1}(k_{t-1}, X_{1,t-1}, T_{t-1}|\overline{h}_{t-1}, n^v). \tag{8}$$

We assume that the fishery manager observes the total harvest, the daily catches, and the total number of harvest days of each vessel during the season without error. Therefore fishery manager 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 length season, T_t. This implies that fishery manager decision 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 consist of 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 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 "attempted" 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 because the intensity of use of the individual capacity depends on the real state of the stock, $X_{1,t} = z_t G(S_{t-1})$.

We analyze the effects of two types of regulatory bodies in this uncertain framework:

a) Regulatory body I, where the fishery manager does not establish the quota for the period. In that case, the fishery will be over at 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 fishery manager establishes the quota,

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

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

Therefore, escapement at the end of the season is the result of individuals' decisions on both capacity use and on the number of days they participate in the fishery during the season, which in turn depends on the regulatory body establishing or not a season quota. In particular, we show numerically below that investment capacity with a season TAC is lower than without a season TAC.

3 The Fishery Manager's Problem

In this section, we present the problem to be solved for the fishery manager. In order to capture the biological orientation of most real world fisheries regulatory bodies, we assume, like Homans and Wilen (1997), that managers have a simple goal. In particular we assume that fishery manager's objective function is to maximize the discounted future harvest.[5]

We start assuming that fishery manager knows the real state of the stock. This allows us to compare optimal policies under each regulatory body with previous literature results based on deterministic models. We show that considering 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 length season T_t that maximizes present value of future catches taking into account stock dynamics (equations (7) and (8)), the capital implementation condition (equation (5)) and the vessel exit decision (equation (6)).

The optimal regulation rule can be obtained in two steps as in the Homans and Wilen' model (2007) if exist a length season T_t that implements any possible quota Q_t. In such case, the optimal rule can also be obtained by solving first

$$\begin{aligned} &\max_{\{Q_t, S_t\}_{t=0}^{\infty}} \quad \textstyle\sum_{t=0}^{\infty} \beta^t Q_t, \\ &s.t. \quad S_t = G(S_{t-1}) - Q_t \end{aligned} \tag{9}$$

and given this quota policy, $Q(X_{1,t})$, fishery manager uses the capital implementation condition (5) to find the optimal vessel capacity k_t. Then the optimal season length, T_t, is the one that satisfies $Q_t(S_{t-1}) = H_t(k_t, G(S_{t-1}), T_t|\overline{h}, n^v)$.

The solution of problem (9) is well known in the literature (see Reed 1979) and implies, in a deterministic world, a constant escapement[6]. The optimal length season rule $T_t(S_{t-1})$

[5]This aim is on the line of the objectives pointed out by the 2002 Johannesburg Summit where it was established 2015 for depleted stocks achieving the maximum sustainable yield.

[6]Note that, the problem is equivalent to find the optimal escapement trajectory that maximizes $\sum_{t=0}^{\infty} \beta^t [G(S_{t-1}) - S_t]$ given the initial condition $G(S_{t-1})$. The Euler equation is equal to $1 = \beta G'(S_t)$, 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, $G'(S^*)$.

implied by problem (9) is given by

$$\begin{cases} T_t(S_{t-1}) = 0 & \text{if} \quad G\left(S_{t-1}\right) < S^*, \\ \\ H_t(k_t, X_{1,t}, T_t|\overline{h}, n^v) = G(S_{t-1}) - S^* & \text{if} \quad G\left(S_{t-1}\right) \geq S^*. \end{cases} \tag{10}$$

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 length season T_t that implements any possible quota Q_t, fishery manager chooses the season length, $T(S_{t-1})$, by solving

$$V(S_{t-1}|\overline{h}, n^v) = \quad \max_{T_t} H_t(k_t, S_t, T_t|\overline{h}, n^v) + \beta V(S_t|\overline{h}, n^v),$$

$$s.t. \begin{cases} \frac{\partial \pi_t(k_t, G(S_t), T_t|\overline{h}, n^v)}{\partial k_t} = p_k, \\ \\ S_t = G(S_t) - H_t(k_t, G(S_{t-1}), T_t|\overline{h}, n^v), \\ \\ exit(G(S_t), |\overline{h}, n^v) = 0. \end{cases}$$

Note that we use dynamic programming (DP) 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.

3.2 Optimal rules under uncertainty

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

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

$$s.t. \begin{cases} \frac{\partial \int_{z_t} \pi(k_t, X_{1,t}, T_t|\overline{h}) f(z_t) dz_t}{\partial k_t} = p_k, \\ \\ S_t = z_t G(S_{t-1}) - H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v), \\ \\ exit(S_{t-1}, T_t|\overline{h}) = 0. \end{cases} \tag{11}$$

where $f(z)$ is the probability density of the random variable z. Observe that fishery manager takes into account that: i) vessels chooses capacity at the beginning of the new season, ii) escapement at the end of the season is a function of the random variable, z_t, and iii) the optimal solution must imply the preservation of the fleet.

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

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

$$s.t. \begin{cases} \frac{\partial \int_{z_t} \pi_t(k_t, X_{1,t}, T_t|\overline{h}) f(z_t) dz_t}{\partial k_t} = p_k, \\ \\ S_t = z_t G(S_{t-1}) - \min\left\{H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v), Q_t\right\}, \\ \\ Q_t = \int_{z_t} H_t(k_t, z_t G(S_{t-1}), T_t|\overline{h}, n^v) f(z_t) dz_t, \\ \\ exit(S_{t-1}, T_t|\overline{h}) = 0. \end{cases} \tag{12}$$

Note that under regulatory body II, the attempted quota must be consistent with the announced season length, the trip limit and the industry investment decisions. Finally, note that when fishery manager uses TACs and fishing periods, sometimes the fishery 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 $i = I, II$, it is necessary to check that each vessel optimally decides do not exit the fishery for the optimal season length rule, $T^i(S)$. Formally we solve

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

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

to check if $exit^i(S_{t-1}, T_t|\overline{h})$ is equal to 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 the European fisheries areas VIIIc and IXa. European authorities do not fixed management objectives for this stock and there is not TAC. However, the stock is managed by Portugues and Spanish authorities through minimum landing size, maximum daily catch, days fishing limitations, and closed areas. Suris (1993) addresses regulatory policies for this stock in a deterministic contex.

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

4.1 Parameter Values and Functional Forms

For our numerical computation, we adopt the following parameter values and functional forms:

1. **Biological dynamics**. As Setthi *et al.* (2005), we assume a logistic growth function for the stock. Under this assumption, the stock dynamics equation (7) 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 are used for estimating the equation. Following the 2007 ICES assessment, we use the period 1996-2006.[7] The results of the estimation are $\widehat{r} = 1.2097$ and $\widehat{L} = 4.5934 \times 10^5$. Figure 1 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 equal to $219,676$ and $357,734$ Tn respectively. Finally, we assume that z_t is an independent, stationary, uniformly distributed random variable of the following form:
$$z_t = 1 + (2u_t - 1)\varepsilon$$
where u_t is drawn from a uniform distribution $[0, 1]$ and ε 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 equal to 40.5%, we decide to fix ε equal to 0.405.

[7] The Stock assessment made by 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 to 2007.

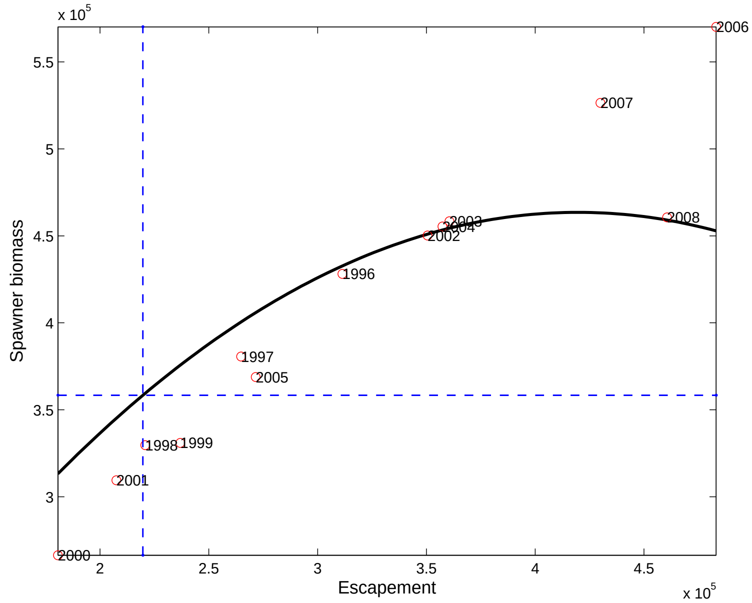


Figure 1: Escapement and Spawner Biomass. Solid line shows the estimated function. Dotted Lines show the constant-escapement solution in a deterministic context. Dotted Lines show optimal levels ($S^* = \widehat{L}[(1+\widehat{r}) - (1+\beta)]/2\widehat{r}$ and $X^* = S^*[(1+\widehat{r}) - (\widehat{r}/\widehat{L})S^*]$ associated with $\beta = .95$, $\widehat{r} = 1.2097$ and $\widehat{L} = 4.5934 \times 10^5$.

2. **Fleet capacity measurement**. Sardine is harvested by Spanish and Portuguese vessels. In northern Spanish waters, sardine is harvested by purse seiners. Half of the purse seiners (51%) are licensed in Galicia (ICES, 2007, section 8.2.1). We calibrate the model to reproduce some stylized facts of the Galician sardine fleet. First, we estimate the daily harvest at vessel level using data on Pesca Galicia[8]. We construct a panel data from daily data starting from January 1, 2007 up to October 31, 2008. Our panel selects vessels that harvest at least 7,000 kilos per season.[9] 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 sardine harvest of vessel i at day d and $u_{id} \backsim N(0, \sigma_u^2)$ represents a time invariant unobserved individual heterogeneity. $Z_{i,d}$ denotes the exogenous variables vector in which a constant term, the gross register tonnage (GRT), in logs, as a proxy of the capacity, and monthly and seasonal dummy variables are included. Table 1 shows the estimation results for the parameter vector δ using OLS.[10] Observe that we obtain an elasticity of the capacity equal to 0.98.

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

[9]7,000 kilos is the daily trip limit of this fishery for the Spanish authorities.

[10]We have also considered individual horse power, size and vessel length. However, none of these variables

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. = 15243; F(11, 15231) = 784.24; Prob > F = 0.0000; R^2= 0.3605

3. **Parameters calibrated from the model**.

The fishing opportunity variable, ξ, is assumed to follow a log normal distribution with $Log\xi - N(0, \sigma_\xi^2)$. The parameter σ_ξ^2 and the boundary values $\underline{\xi}$ and $\overline{\xi}$ are calibrated in such way that the stylized facts of 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,

$$\begin{aligned}
D_1 &= \overline{h}\left\{\int_{\underline{\xi}}^{\overline{\xi}} \frac{\xi}{\overline{\xi}} f(\xi)\, d\xi + \int_{\overline{\xi}}^{\infty} f(\xi)\right\} d\xi, \\
D_2 &= \int_{\overline{\xi}}^{\infty} f(\xi)\, d\xi, \\
D_3 &= \int_{\underline{\xi}}^{\infty} f(\xi)\, d\xi.
\end{aligned}$$

Notice that the average daily harvest rule, when the fleet harvest less than $\overline{h}$, is expressed as $\xi\overline{h}/\overline{\xi}$ taking in consideration (**??**) and (2).

are statistically significative. Notice that it only appears a season dummy (year) because 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

Once the boundary values $\underline{\xi}$ and $\overline{\xi}$ have been calibrated, given a guess of α, the parameters, c_f, θ and γ can be calculated using the definitions of the boundary of ξ, equations (2) and (3) and the elasticity of capacity (see equation (1)). That is,

$$
\begin{aligned}
c_f &= (1-\gamma)\bar{h}\underline{\xi}/\overline{\xi}, \\
\theta &= \frac{[\bar{h}/\overline{\xi}]^{1-\gamma}}{Xk^{\alpha}(\gamma/w)^{\gamma}}, \\
D_4 &= \frac{\alpha}{1-\gamma}.
\end{aligned}
$$

where $X = 526,457$, $k = exp(3.4)$ and $w = 1/0.9$ are the 2007 biomass, average GRT and the average real cost of fleet sample, respectively[11]. Finally, we use equation (5) to check if the guess value used for α implements the level of capacity.

Given all the parameters, it is possible to calculate the harvest path and simulate the stock evolution intra season using the dynamic equation (4). The average value of the daily harvest, $h_{d,t}$, and the fractions of restricted days are calculated to mimic the average data of the fishery along the season. The season length is fixed to reproduce the total captures of the 130 vessels of the sample. Figure 2 shows the inter and intra season harvest and stock dynamics for the calibrated parameters.

To close the calibration, we considered a discount factor $\beta = 0.95$ which is equivalent to a discount rate of 5.26%; a trip limit equal to $\overline{h} = 7$ Tn which is the value imposed by the Spanish authorities for the Iberian sardine; a rental capital price equal to $p_k = 5.25\%$; $[\underline{k}, \overline{k}] = [0.85 \times 30, 1.15 \times 30]$ being 30 the average GRT of the sample, and a capital share, $\phi = 0.5$. Table 3 summarizes the parameter values used for the benchmark model.

[11]Along 2007, sardine prices per day was quite constant around (0.9 euros per kilo).

Table 3: Model Parameter Calibration

θ	daily harvest	1.5241×10^{-7}
γ	daily effort returns	0.1138
α	capacity returns	0.87
c_f	daily fix cost	1.1186
σ_ξ	fishing daily opportunity	0.7453
$\overline{h}$	daily trip limit	7
ϕ	owner share	0.5
p_k	capacity price	.10
β	discount factor	0,95
r	stock growth rate	1.2097
L	carrying capacity of the stock	4.5934×10^{5}
ϵ_z	stock uncertainty	0.4050

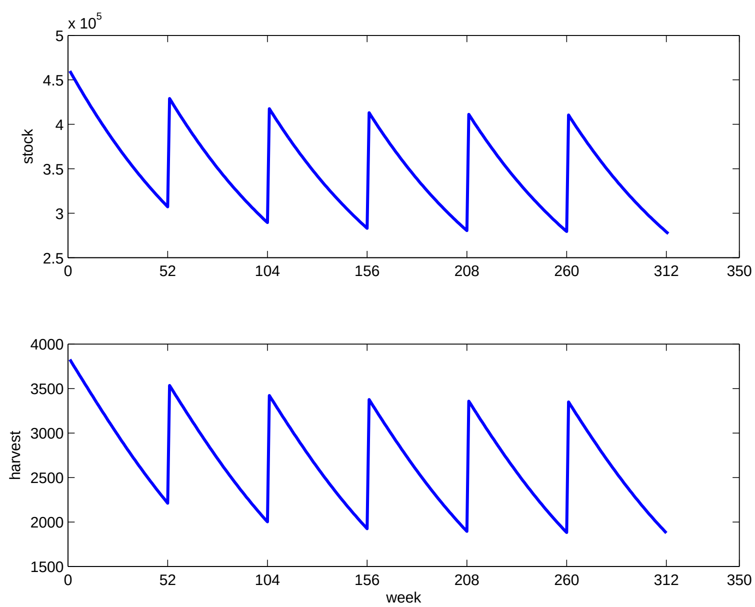


Figure 2: Intra and inter season dynamics with the calibrated parameters.

4.2 Simulation strategy. Codes

Codes for the simulation of the fishery behavior have been written in Matlab. The simulation strategy for finding the optimal rules for the season t follows the next algorithm:

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

2. A partition in 52 weeks for the season length T is defined. For any value of the T and for each possible value of escapement S_{t-1} and the state of the stock z_t which implies a stock $X_{1,t} = z_t G(S_{t-1})$, the following actions are done:

   (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 aggregated harvests, $h_{d,t}$ is calculated for any k_t using the value of n^v.

   (c) The next daily stock is calculated substracting the daily aggregated captures from the initial stock.

   (d) The season profits of each vessel, π_t, is calculated adding the profits of the T weeks in which the season is open.

   (e) The investment problem for each vessel is solved at de beginning of the season. That is k_t is calculated using (5) for the associated $X_{1,t}$, T, n^v and $\overline{h}$.

   (f) The daily aggregated harvests and profits functions, $h_{d,t}$ and $\pi_{d,t}$, are recalculated for the optimal k_t obtained from the investment problem.

   (g) The season aggregated harvests and profits functions, H_t and Π_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 (11) and (12)).

4. Given the optimal season length, individual vessel profits are calculated for the whole season. Based on this result, each vessel decides to exit or not the fishery by solving the DP (13). It is verified that for each regime i, the exit function $exit(S_{t-1}, T_t|\overline{h})$ is equal to zero.

5. When a TAC regime is considered, the optimal season length, T_t^{II}, is replaced in the aggregated harvest function to calculate the TAC that close the fishery,

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

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 the use or not of TACs). In this section we present numerical simulations of the model to show the relationships between the variables.

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

5.1 The season length rule

Deterministic model

When there is not uncertainty about the state of the resource and there is none 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 dynamics 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 does depend upon 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 is 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 3 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[12]. The left panel shows a three dimensional graph with optimal season length (in weeks) for different combinations of stocks and number of vessels. We can see that as the stock of the resource and the number of licences increase, the optimal season length increases. In the right panel, we show 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 color), *ii)* The fishery is never open during the season (dark blue), *iii)* The fishery closes at some moment of the season (light blue). The white dotted line shows the situation

[12]Simulations have been run assuming $\epsilon_z = 0$, everything else equal.

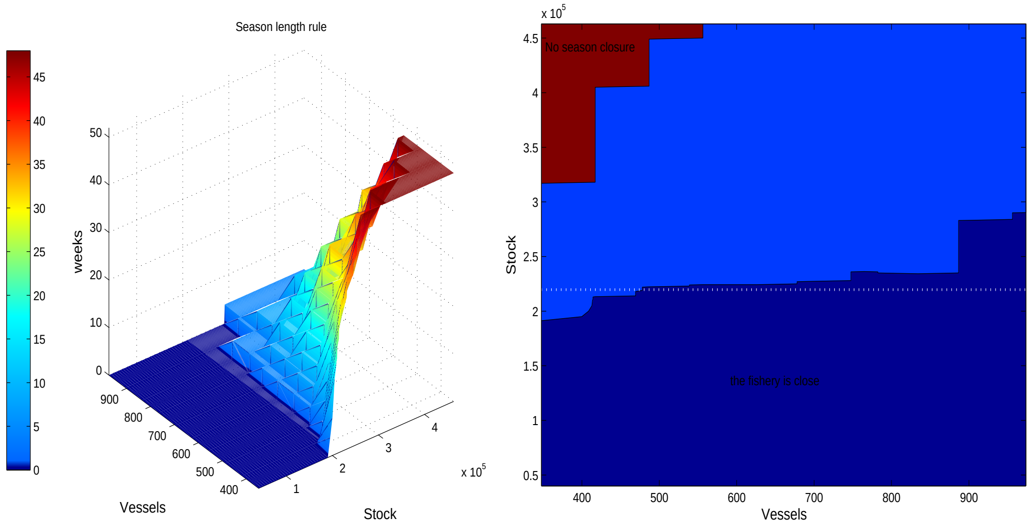
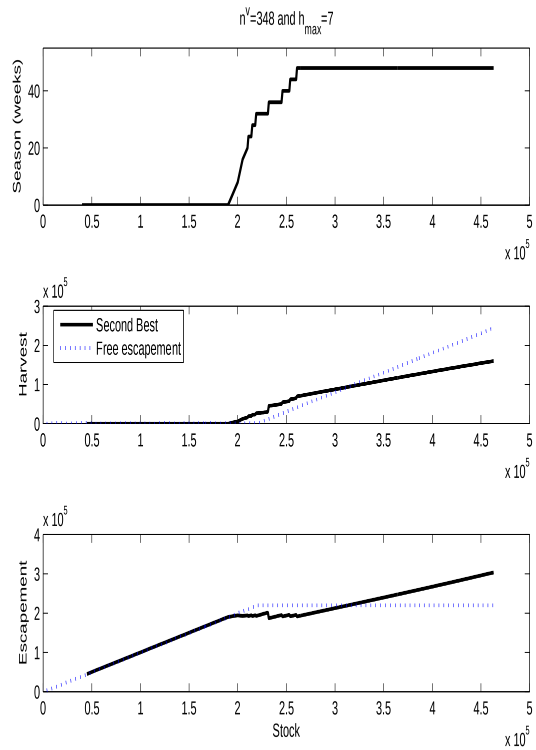


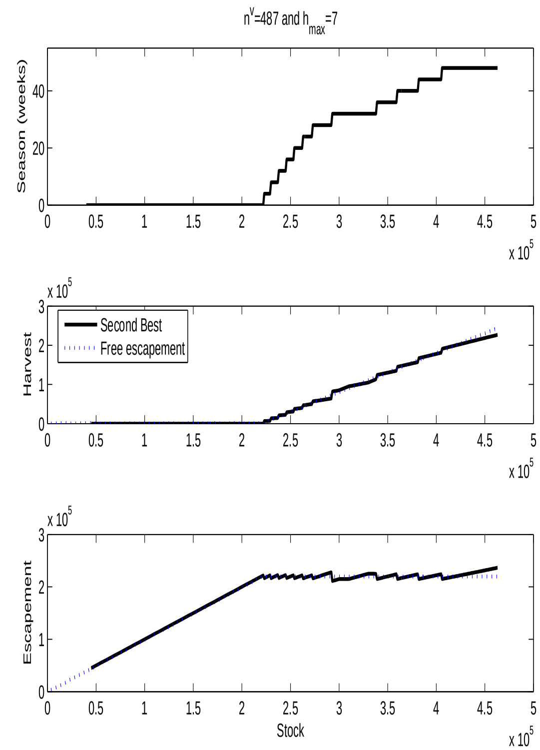
Figure 3: Deterministic model with respect to the state of the stock. Left panel: $T(X_{t,1}, n^v|\overline{h} = 7)$ rule. Right panel: T rule vs. free escapement rule (white dotted line)

of constant-escapement; below (above) the dotted line the constant-escapement rule would imply the closure (openness) of the fishery. The results are quite intuitive. When the stock is high and the number of licences is low, the fisheries can be opened during the whole season because the total harvest is not high enough to close the fishery. By the contrary, regardless of the number of licences, the fisheries remains closed during the whole season whenever the stock of the resource is below around 200 thousand tones. Nevertheless, there are small areas where the optimal endogenous model implies the total closure of the fishery while the constant-escapement policy would imply its partial openness and the other way around.

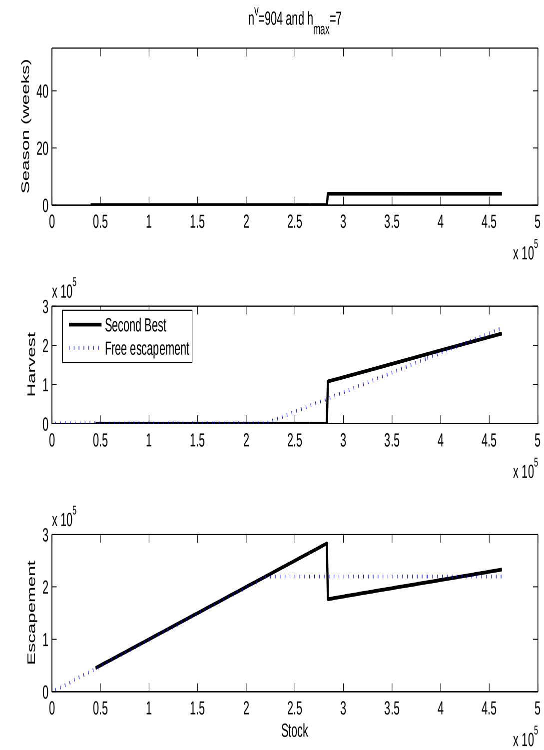
Figure 4 compares the optimal solution for season lengths, harvests and escapements for different stocks with those implied by the constant-escapement solution (10). In particular, we show the optimal solutions for a low number of vessels ($n^v = 348$, panel a), for a medium number of vessels ($n^v = 487$, panel b) and for a high number of vessels ($n^v = 904$, panel c). For the harvest and the escapement, the constant-escapement solution is shown in blue doted line. We observe that when the number of licences is small (Figure 4 panel a), the optimal solution differs from constant-escapement because the harvest associated to the steady state solution cannot be captured with the small capacity of the fleet. Because of this, from the regulator point of view, it is optimal to allow higher harvests and maintain the fishery opened more time comparing with the constant-escapement solution.



(a) small number of vessel



(b) medium number of vessels



(c) large number of vessels

Figure 4: Optimal harvests, escapement and length seasons as function of stock. Deterministic model with respect to the state of the stock.

When the number of licensed vessels increases to a medium value (Figure 4 panel b), the optimal rule is similar to the constant-escapement solution. The petty differences appear because the season length is not a continuos variable because it is fixed in weeks. Finally, when the number of vessels is very high (Figure 4 panel c), the optimal rule cannot sustain the steady state solution of constant-escapement. Even, if the fishery is opened for a short period, the fleet harvests more than desirable. In this case, the optimal rule may generate cycles: the fishery is close for stocks higher than those from constant-escapement and when it is opened the harvest is higher than constant-escapement.

The right panel of Figure 3 summaries this information. Observe that for high levels of the stock, an increase of the number of vessel leads the regulator to close the fishery although there is no extinction risk. In the same way, for levels of the stock below but near to the constant-escapement level, the regulator may decide not to close the fishery if the number of vessels is small.

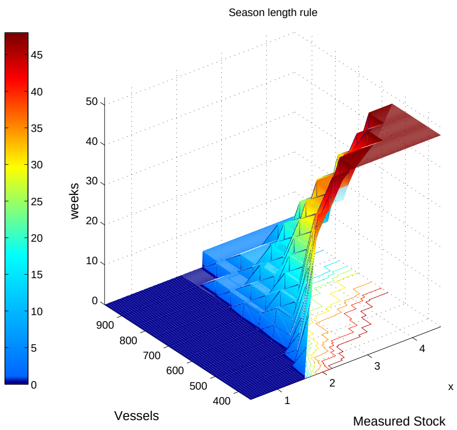
Uncertainty from inaccurate stock estimations

When stock uncertainty arises from inaccurate stock estimations the optimal policy is no longer constant-escapement rules (Clark and Kirkwood, 1986). Moreover, Sethi *et al.* (2005) point out that "While optimal policy suggest lower escapement in the middle range, it advocates higher escapement in the last range". In order to verify if these results appear in our model, we compare the optimal rules with the constant-escapement solution assuming uncertainty about the state of the resource. Furthermore, we show how the optimal rules depend on TACs being considered a management instrument or not.

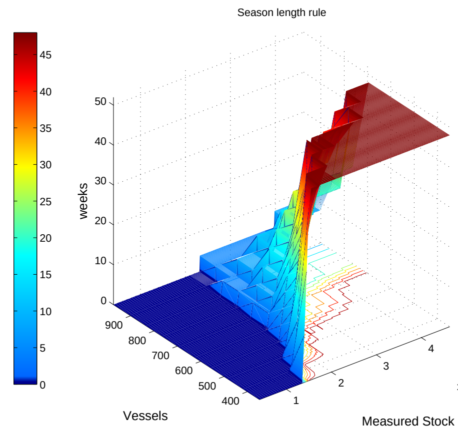
Figure 5 mimics the results of Figure 3 but considering an uncertain scenario with respect to the stock[13]. The left panel shows the results when managers do not establish TACs for regulating the fishery (regulatory body I). In the right panel, results assuming that the fishery managers establish additionally *ex-ante* TACs (regulatory body II) are illustrated.

Comparing the right panel in Figure 5 with Figure 3, we can see how much the results depend on uncertainty. It is clear that the higher the uncertainty about the state of the stock is, the lower the probability of closing the fishery is (the red area increases and the dark blue area reduces with the uncertainty). Therefore, our results are on the same line that Sethi *et al.* (2005). Furthermore, comparing left panel with right panel in Figure 5, we can see how much the results depend on TACs being considered an instrument. We observe that using TAC as a management instrument increases the optimal season length.

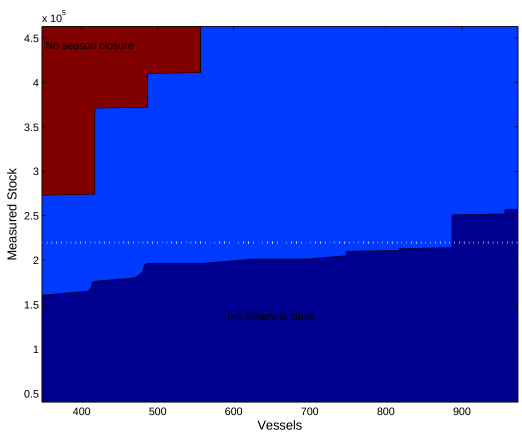
[13]Simulations have been run assuming $\epsilon_z = 0.4050$, everything else equal. In section 4.1, we explain how this value has been selected.



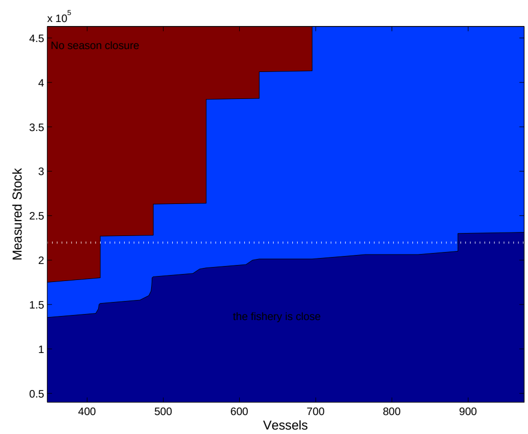
(a) without TAC



(b) with TAC



(c) without TAC

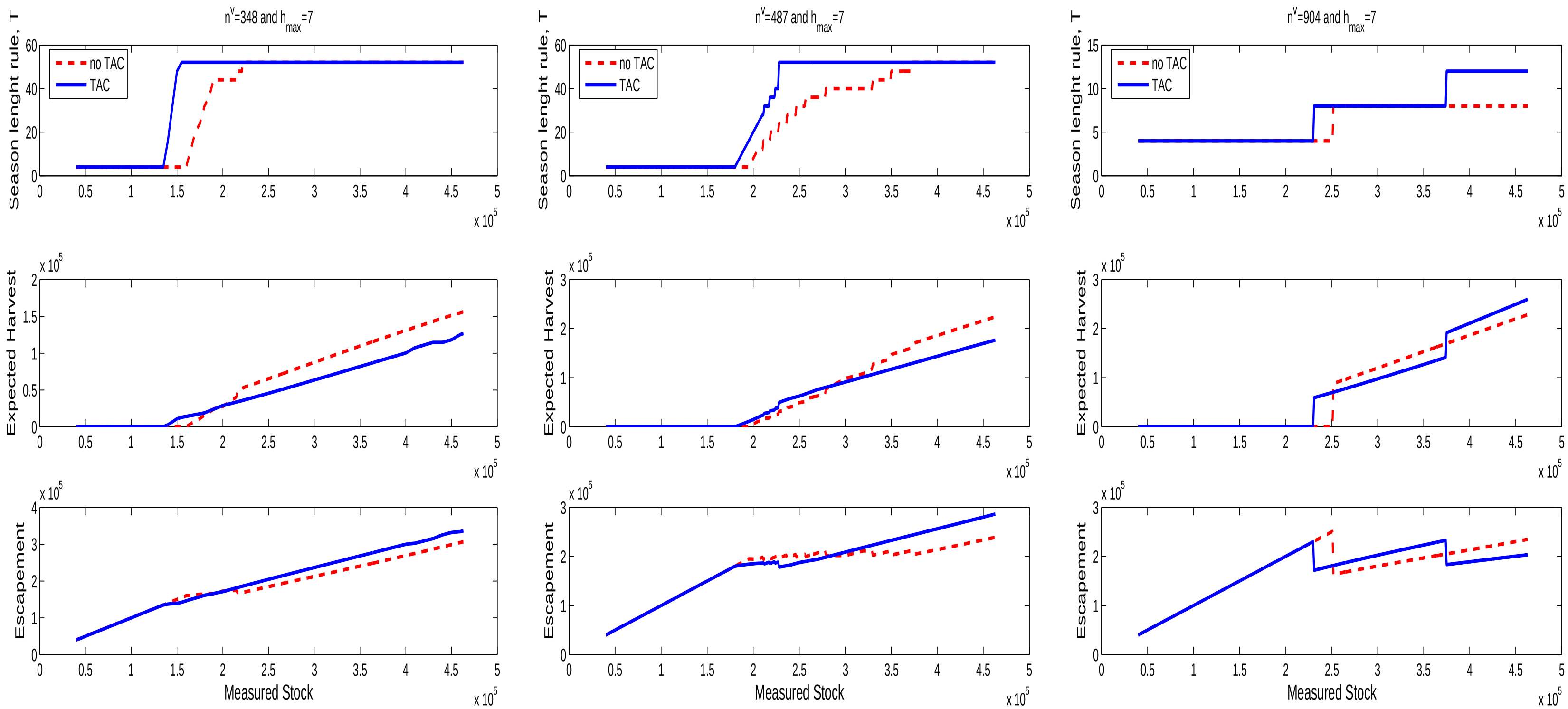


(d) with TAC

Figure 5: Model with uncertain stock. Upper panel: $T(X_{t,1}, n^v|\overline{h} = 7)$ rule. Lower panel: T rule vs. constant-escapement rule (white dotted line)

Figure 6 compares the optimal season lengths, harvests and escapements for different stocks under the two types of regulatory bodies analyzed. Blue lines illustrate the regulatory body I (with TAC). Red lines show the regulatory body II (without TAC). In particular, we show the optimal solutions for a low number of vessels ($n^v = 348$, panel a), for a medium number of vessels ($n^v = 487$, panel b) and for a high number of vessels ($n^v = 904$, panel c). Notice that under uncertainty, optimal harvests and escapement are calculated in expectations. Therefore, the expected values under the regulatory bodies I and II are different because both, the optimal season length and the dynamics, are different. Formally,

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



(a) small number of vessel

(b) medium number of vessels

(c) large number of vessels

Figure 6: Model with uncertain stock. Optimal Harvests, Escapement and Length Seasons as Function of Stock.

Figure 6 highlights important findings. First, as it appears in Figure 5, the optimal season length is higher when TACs are used as management instrument than when it is not. And this is true for any number of vessels and for any measured stock. This is so because when managers use TACs, the fishing period may be fixed larger to cover unexpected bad fishing opportunities. In the case that fishing opportunities are better than expected and vessels harvest more that expected, then the fishery is closed earlier, just when the TAC is exhausted. Second, 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. Notice that when regulators do not use TACs, season lengths are shorter than with TACs and vessels select higher capacities to maximize future profits. This implies the fleet ends up fishing more and the escapement reduces more that with TACs.

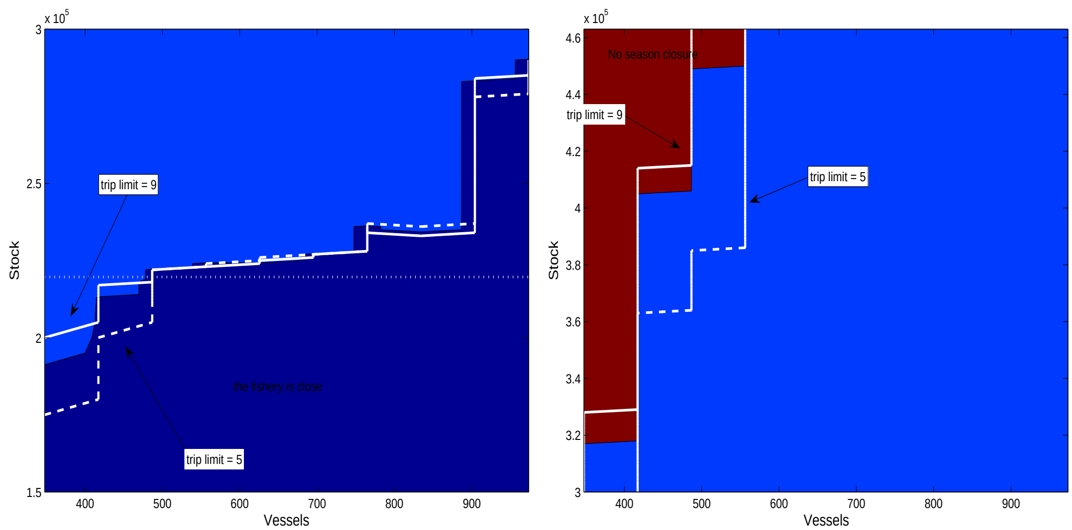
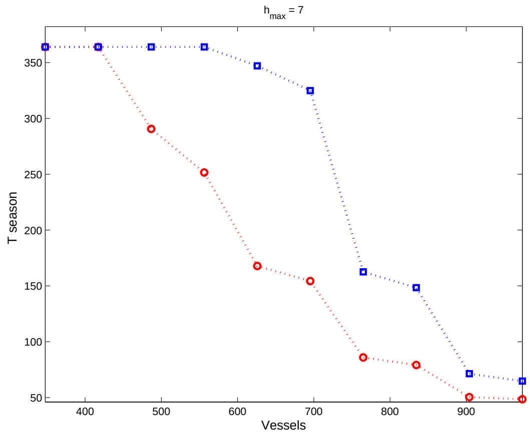


Figure 7: Effects of changes in the trip limit parameter

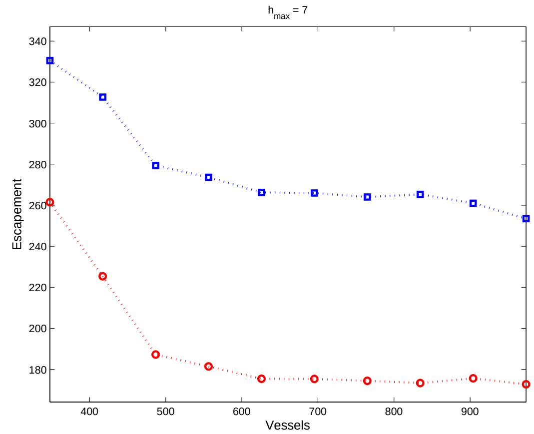
Trip limits

Finally, we analyze how changes in the trip limit parameter vary the optimal season length. Figure 7 illustrates the effects of the changes in the parameter $\overline{h}$ over the fishery closure for different combinations of vessels and stock. This figure is the same that the right panel in Figure 3 but divided in two parts. The left panel of Figure 7 corresponds to the lower part of the graph in the right panel in Figure 3 (stock from 1.5×10^5 to 3×10^5). The right panel of Figure 7 corresponds to the upper part of the graph in the right panel in Figure 3 (stock from 3×10^5 to 4.6×10^5).

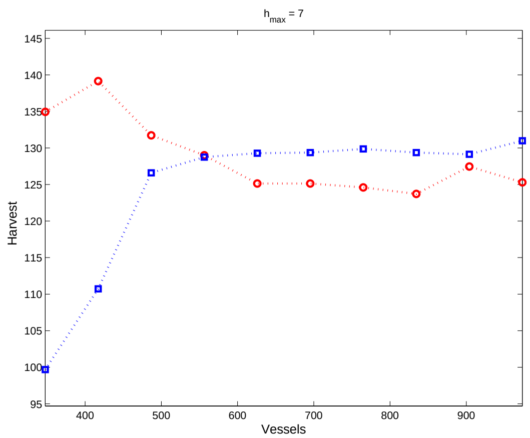
Figure 7 shows how the boundary for seasonal closures moves when trip limit parameter



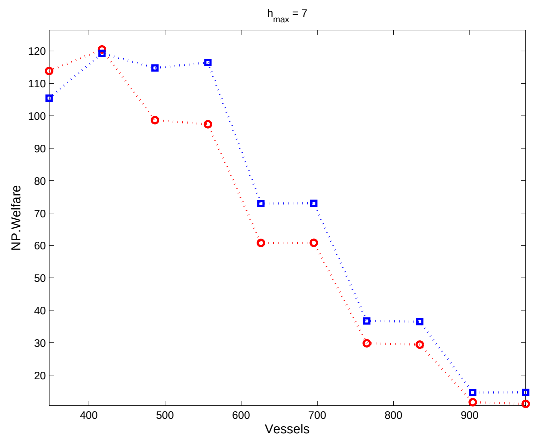
(a) Season length



(b) Escapement



(c) Harvest



(d) Welfare

Figure 8: Main variables under the Regulatory Bodies I (no TAC, red line) and II (TAC, blue line)

varies from the benchmark value $\overline{h} = 7$ to $\overline{h} = 5$ and $\overline{h} = 9$. Notice that upper movements means that the stock has to be higher to close the fishery for a given number of vessels. Movements to the right shows that the number of vessels has to be higher to close the fishery for a given a stock. The main result is that lower trip limits imply larger season lengths with lower probability for the fishery closure.

5.2 Properties of each management regime

Once the optimal season length are obtained, we are able to compare the effect of each regimen body in biological (stock and escapement) and economic (profits and welfare) terms. In order to do this, we implement 100 times the optimal season length for each regulatory body. Since under uncertainty, there exists risk of extinction, we run each simulation for a long period (1000 seasons). The experiment is run for fisheries which are different among them by the number of licences[14].

In order to select the number ol licences analyzed, we start by calculating the minimum number of vessels that, fishing every day, would generate agregate captures compatible with the harvest of the resource analyzed. For the case of the Iberian sardine this number corresponds with 348 licences. Then we run the simulations increasing the number of licences in a 20%, 40% and so on until 180%.

In all the implementations, the initial measured stock is taken equal to the level of constant-escapement policy in a deterministic set up ($G(S^*) = 357,743$ Tn). Since under uncertainty, there exist risk of extinction, we run each simulation for a long period (1000 seasons). To discount the future we use, as Sethi *et al.* (2005), a discount factor equal to 0.95. We summarized 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 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 Figure 8 shows the average of the relevant variables for the 100 simulations run for the two regulatory bodies and considering 10 different numbers of licences. Red lines illustrate the regulatory body I (without TAC). Blue lines show the regulatory body II (with TAC). The figure highlights relevant findings. First, the higher the number of vessels is, the lower the season length, the escapement, the harvest, individual profits and the welfare, 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, profits and welfare. However, when the fleet is large using TACs along with fishing periods leads to increase both biological and economic variables.

Finally Table 5 shows the cv associated to the 100 simulations run for the two regulatory bodies and considering 10 different numbers of licences. Two empirical facts highlight from the results. First, the use of TACs along with fishing periods reduces de variability of all the variables simulated for medium and high number of licences. Second, the cv is more

[14]The experiment has been also run for different trip limit values. However, the results are qualitatively similar for all the values. So, we have decided to show only the results for the benchmark parameter, $\overline{h} = 7$ in the main text. Table 6 in the Appendix shows in detail the value of all statistics for all the cases analyzed.

Table 4: Means ($\overline{h} = 7$)

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
NP.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
NP.Welfare										
-with TAC	113829	120468	98667	97390	60788	60794	29816	29390	11628	11093
-with TAC	105461	119302	114764	116444	72941	73016	36698	36481	14600	14680

100 simulations of 1000 periods

Table 5: C.V. ($\overline{h} = 7$)

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 1000 periods

sensitive to changes in the number of licences when TACs are not used that when they are used. For instance, without TACs, the cv of harvest goes from 0.60 to 1.01 depending on the number of licences. However, with TACs, the cv of harvest goes from 0.50 to 0.55.

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

5.3 The fleet size

As we can see in Table 4, the size of the fleet is a relevant variable that affect the results. In particular, we can see that the maximum welfare is reached when the fleet has a medium size. In fact, if the regulator could select the number of licences he/she would choose to hand over 417 vessels regardless of the regulatory body. It is worth mentioning that in both cases, the optimal season length implies that the fishery is open the whole year around.

These results do not change qualitative when the trip limit varies. Table 6 sumarizes the welfare of the fisheries for the two regulatory body assuming three different trip limits ($\overline{h} = 5, \overline{h} = 7, \overline{h} = 9$). We mark in bold the maximum welfare under each scenario studied. Notice that the minimum fleet size ($n^v = 348$) is never the one that leads to the maximum welfare because the size capacity may not be enough to capture the available harvest. On the other hand, whenever the number of licences implies the maximum welfare, it is optimal not restricting the access to the fishery (see Table 6 in the Appendix). In the ligth of these results we may conclude that the regulator would rather select the number of licences and do not restrict the season length.

5.4 Extinction

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

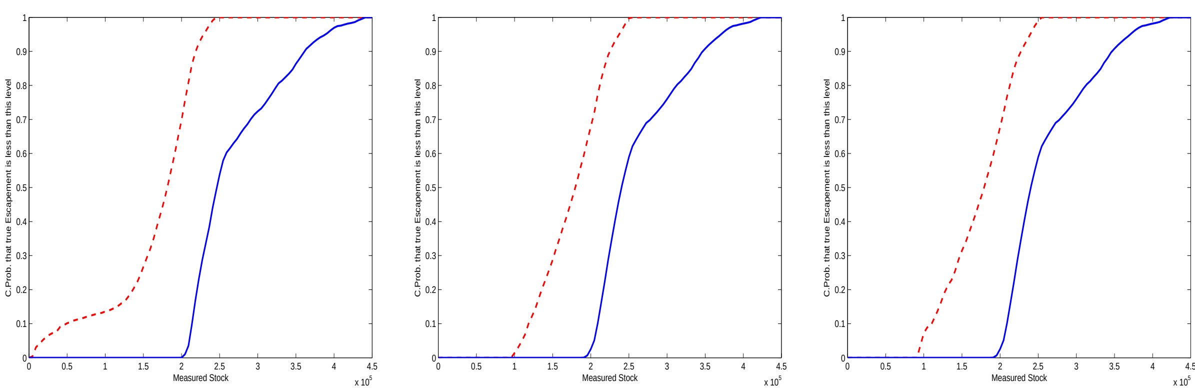
By the contrary, the risk of extinction may show up when the fishery is characterized by a combination of high stocks and large number of licences. The extinction risk really appears when large measurement stocks lead vessels to participate more days and to harvest more per day. If the fishery is regulated only with fishing periods, the fleet may find profitable to harvest too much in a short period of time and the stock may disappear if the number

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 1000 periods

of vessels is high enough. This negative effect does not appear when the number of vessels is small. However, when the fishery is regulated using TAC along with fishing periods, the extinction risk disappears because once the quota is exhausted the fishery is closed and the stock is not depleted. In this sense we can say that the introduction of TACs as management instrument avoids the risk of extinction.



(a) $\overline{h} = 5$ (b) $\overline{h} = 7$ (c) $\overline{h} = 9$

Figure 9: Risk of Extinction. Probabiity $S < X$

Figure 9 illustrates the relationship between the measured stock and the probability of the *ex post* escapement to be below the stock. Red lines illustrate the relationship under regulatory body I (without TAC). Blue lines show it under the regulatory body II (with TAC). We highlight the following results: *i)* The probability that the escapement is below

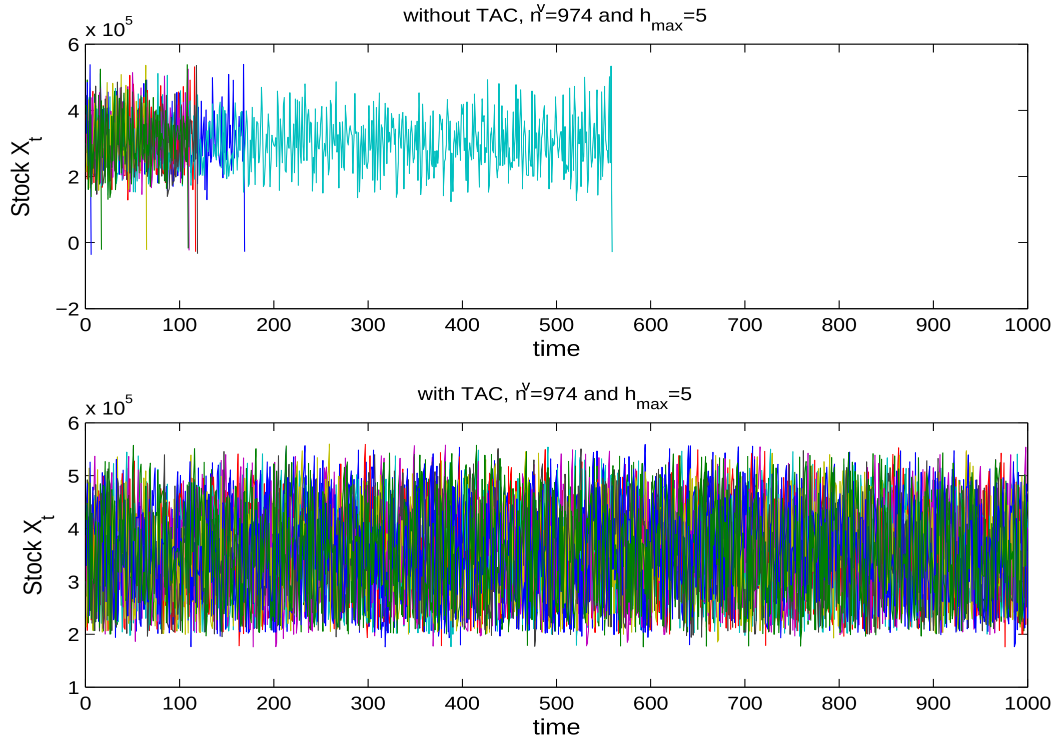


Figure 10: Risk of Extinction for Large Fleets

the stock is always higher when TACs are not used as management instrument. *ii)* When the stock is high enough the probability that the escapement is below the stock is one and therefore extinction is sure. *iii)* When the stock is low, there is not risk of extinction regardless of the regulatory body considered.

These results can be also appreciated in Figure 10. This figure illustrates the evolution of the stock along the 1000 periods simulated under regulatory body I (without TAC, upper panel) and under regulatory body II (with TAC, low panel) for the case of a large fleet.

Each color shows a particular simulation. We can see that without TACs, in many simulations the stock drops to zero level and extinction becomes real. However, with TAC, this situation never happens.

6 Conclusions

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

With respect to uncertainty, we found that higher levels of uncertainty about the state of the stock reduce the likelihood of closing the fishery. Therefore, our result is on the same line that as Sethi et al. (2005).

The use of TACs as management instrument in fisheries already regulated with fishing periods leads to larger optimal season lengths and harvests, especially for medium and high number of licences. However, its effect over the 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 leads to increase all biological and economic variables. Moreover, the introduction of TACs as management instrument avoids the risk of extinction. The risk of extinction appears in our model whenever the fishery is characterized by a combination of high stocks and large number of licences. Large measurement stocks lead vessels to participate more days and to harvest more per day. If the fishery is regulated only with fishing periods, the fleet may find 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 once the quota is exhausted the fishery is closed and the stock is not depleted.

When we focus on welfare, we find that from the regulator point of view, it would be better selecting the number of licences and do not restrict the season length. Therefore a interesting issue to be analyzed in future research is how this optimal number of licenses is achieving given the initial situation of the fleet. In fact some studies suggest that in many stocks there is excess capacity (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 a endogenous variable that depends on the technical change growth rate.

Another interesting regulation question to be addressed would be the role of the mesh size regulations and/or how to share the TAC between different gear. Diekert *et al.* (2010) suggest that some commercial fisheries are wasting a large part of its potential rather a too small mesh size than excessive effort. Our model could be extended by introducing more realistic age structured resource dynamics, as Tahvonen (2009) and Bjørndal *et al.* (2004), to study the effects of changes in mesh sizes by using the methods developed in Da Rocha et al. (2010) and Da Rocha and Gutierrez (2010).

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Table 7: Experiments

n vessels	347.68	347.68	417.22	417.22	486.76	486.76	556.29	556.29	625.83	625.83	695.37	695.37	764.90	764.90	834.44	834.44	903.98	903.98	973.51	973.51
$\bar{h}=5$																				
TAC	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
T season	364.00	364.00	364.00	364.00	363.86	364.00	350.11	364.00	179.84	357.74	164.72	337.95	88.97	171.04	85.35	156.76	50.32	79.22	7.52	70.43
c.v.	0.00	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.39	0.04	0.38	0.07	0.33	0.11	0.33	0.13	0.25	0.13	3.99	0.20
Quota	123.61	129.58	131.19	142.76	132.67	166.90	125.65	171.25	99.15	184.11	99.30	184.15	98.64	183.10	100.74	185.89	104.83	172.87	16.64	177.80
c.v.	0.08	0.07	0.06	0.07	0.06	0.10	0.17	0.11	0.53	0.19	0.52	0.19	0.54	0.20	0.54	0.19	0.50	0.13	4.33	0.14
Stock	414.39	432.58	393.67	426.94	346.10	411.33	333.72	405.07	301.03	393.96	301.11	393.93	299.23	393.61	300.16	391.63	283.18	395.37	44.40	389.39
c.v.	0.27	0.26	0.26	0.27	0.26	0.27	0.27	0.27	0.34	0.27	0.34	0.27	0.34	0.27	0.34	0.27	0.42	0.27	4.11	0.28
Escapement	290.42	341.09	259.17	325.24	208.56	292.31	198.40	282.28	175.29	264.60	175.36	264.57	174.10	264.43	174.68	261.55	164.36	269.21	25.62	260.75
c.v.	0.16	0.22	0.12	0.22	0.06	0.21	0.11	0.21	0.26	0.19	0.26	0.19	0.27	0.19	0.27	0.19	0.36	0.22	4.12	0.21
Harvest	123.97	91.49	134.50	101.69	137.53	119.02	135.32	122.78	125.74	129.36	125.75	129.36	125.13	129.19	125.48	130.08	118.82	126.16	18.79	128.63
c.v.	0.54	0.48	0.57	0.47	0.71	0.49	0.76	0.50	1.02	0.56	1.02	0.57	1.03	0.57	1.03	0.57	1.03	0.50	5.49	0.52
Profits	14.55	13.32	13.39	12.45	10.22	10.45	8.98	9.49	4.72	5.80	4.24	5.23	1.88	2.36	1.72	2.18	0.55	0.79	0.08	0.73
c.v.	0.45	0.37	0.48	0.37	0.63	0.45	0.70	0.48	0.98	0.57	0.98	0.57	1.02	0.58	1.03	0.58	1.28	0.57	6.08	0.62
NP.Profits	274.65	251.90	253.41	235.65	195.86	197.47	173.04	179.56	92.22	109.67	82.91	98.81	36.87	44.65	33.73	41.27	11.05	14.83	10.09	13.84
NP.Welfare	95.49	87.58	105.73	98.32	95.34	96.12	96.26	99.89	57.71	68.64	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
$\bar{h}=7$																				
TAC	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
T season	364.00	364.00	364.00	364.00	290.44	364.00	251.56	364.00	167.30	346.93	153.54	324.79	85.53	162.50	78.93	148.37	48.22	71.43	48.39	64.79
c.v.	0.00	0.00	0.00	0.00	0.16	0.00	0.27	0.00	0.39	0.06	0.38	0.09	0.34	0.12	0.33	0.10	0.32	0.19	0.26	0.20
Quota	129.13	142.92	131.95	160.24	112.55	188.43	103.86	191.92	98.12	184.12	98.15	184.46	99.68	185.79	97.41	184.90	103.28	179.36	105.17	183.65
c.v.	0.07	0.08	0.03	0.09	0.34	0.10	0.45	0.14	0.54	0.18	0.53	0.18	0.56	0.19	0.57	0.16	0.62	0.14	0.64	0.15
Stock	396.10	429.88	364.31	423.08	318.77	405.51	310.27	401.86	300.16	394.98	299.94	394.78	298.55	393.34	297.03	394.03	289.55	389.59	297.56	383.87
c.v.	0.26	0.26	0.26	0.27	0.29	0.27	0.31	0.27	0.34	0.27	0.34	0.27	0.35	0.27	0.36	0.27	0.40	0.28	0.33	0.28
Escapement	261.36	330.20	225.35	312.40	187.13	279.03	181.26	273.26	174.94	265.90	174.73	265.59	173.86	263.67	173.04	264.88	167.77	260.58	172.40	253.07
c.v.	0.10	0.21	0.03	0.20	0.17	0.17	0.21	0.17	0.27	0.19	0.27	0.19	0.28	0.19	0.29	0.19	0.32	0.21	0.26	0.20
Harvest	134.75	99.68	138.96	110.68	131.64	126.48	129.00	128.59	125.22	129.09	125.22	129.19	124.69	129.67	123.99	129.15	121.78	129.01	125.16	130.81
c.v.	0.60	0.50	0.65	0.51	0.86	0.55	0.94	0.57	1.04	0.56	1.04	0.57	1.05	0.57	1.05	0.56	1.02	0.52	1.00	0.55
Profits	17.32	16.02	15.16	15.12	10.46	12.49	9.01	11.10	4.97	6.19	4.47	5.58	1.99	2.54	1.80	2.31	0.62	0.85	0.57	0.79
c.v.	0.53	0.42	0.60	0.44	0.82	0.53	0.89	0.56	1.01	0.59	1.01	0.59	1.06	0.60	1.08	0.60	1.24	0.62	1.30	0.67
NP.Profits	327.52	302.66	288.63	285.45	202.67	235.57	175.08	209.28	97.16	116.79	87.43	105.17	38.88	47.93	35.29	43.68	12.79	16.10	11.34	15.06
NP.Welfare	113.87	105.23	120.42	119.10	98.65	114.66	97.40	116.42	60.80	73.09	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
$\bar{h}=9$																				
TAC	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
T season	364.00	364.00	364.00	364.00	268.97	364.00	231.68	364.00	163.60	343.56	147.36	320.87	83.22	157.96	77.02	147.28	49.54	68.63	47.49	63.56
c.v.	0.00	0.00	0.00	0.00	0.22	0.00	0.32	0.00	0.40	0.06	0.39	0.10	0.34	0.12	0.32	0.10	0.24	0.20	0.27	0.20
Quota	128.71	148.22	129.43	165.07	107.97	191.20	101.39	193.65	97.97	184.41	96.66	184.72	98.50	185.31	96.39	185.78	106.24	181.71	102.60	185.59
c.v.	0.05	0.09	0.05	0.09	0.41	0.12	0.50	0.14	0.54	0.19	0.55	0.19	0.57	0.18	0.56	0.18	0.58	0.15	0.69	0.15
Stock	383.93	427.05	352.22	420.30	314.28	405.38	307.10	402.49	299.36	395.66	299.06	395.37	296.75	394.23	296.67	393.88	299.33	387.52	292.52	381.74
c.v.	0.26	0.27	0.26	0.27	0.30	0.27	0.32	0.27	0.35	0.27	0.35	0.27	0.36	0.27	0.36	0.27	0.32	0.28	0.34	0.28
Escapement	246.18	322.86	214.08	306.21	184.07	278.22	179.44	273.78	174.51	266.68	174.30	266.26	172.86	264.93	172.76	264.47	173.39	257.62	169.11	250.27
c.v.	0.06	0.21	0.05	0.20	0.20	0.17	0.24	0.16	0.28	0.19	0.28	0.19	0.29	0.19	0.29	0.19	0.25	0.20	0.28	0.20
Harvest	137.75	104.18	138.14	114.10	130.22	127.15	127.66	128.71	124.84	128.98	124.75	129.11	123.89	129.30	123.92	129.41	125.94	129.90	123.40	131.48
c.v.	0.64	0.50	0.70	0.52	0.91	0.57	0.99	0.58	1.05	0.57	1.05	0.57	1.06	0.57	1.05	0.57	0.98	0.53	1.05	0.56
Profits	18.64	17.49	15.75	16.26	10.69	13.21	9.18	11.68	5.07	6.36	4.55	5.73	2.02	2.60	1.84	2.39	0.65	0.89	0.57	0.83
c.v.	0.59	0.46	0.67	0.48	0.88	0.56	0.96	0.58	1.03	0.61	1.04	0.61	1.08	0.61	1.08	0.61	1.22	0.65	1.37	0.69
NP.Profits	352.80	329.77	300.80	306.42	207.43	248.68	178.65	219.90	98.97	119.86	88.98	108.06	39.54	49.14	36.18	44.88	12.87	16.75	11.40	15.66
NP.Welfare	122.66	114.66	125.50	127.84	100.97	121.05	99.38	122.33	61.94	75.01	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

100 simulations of 1000 periods

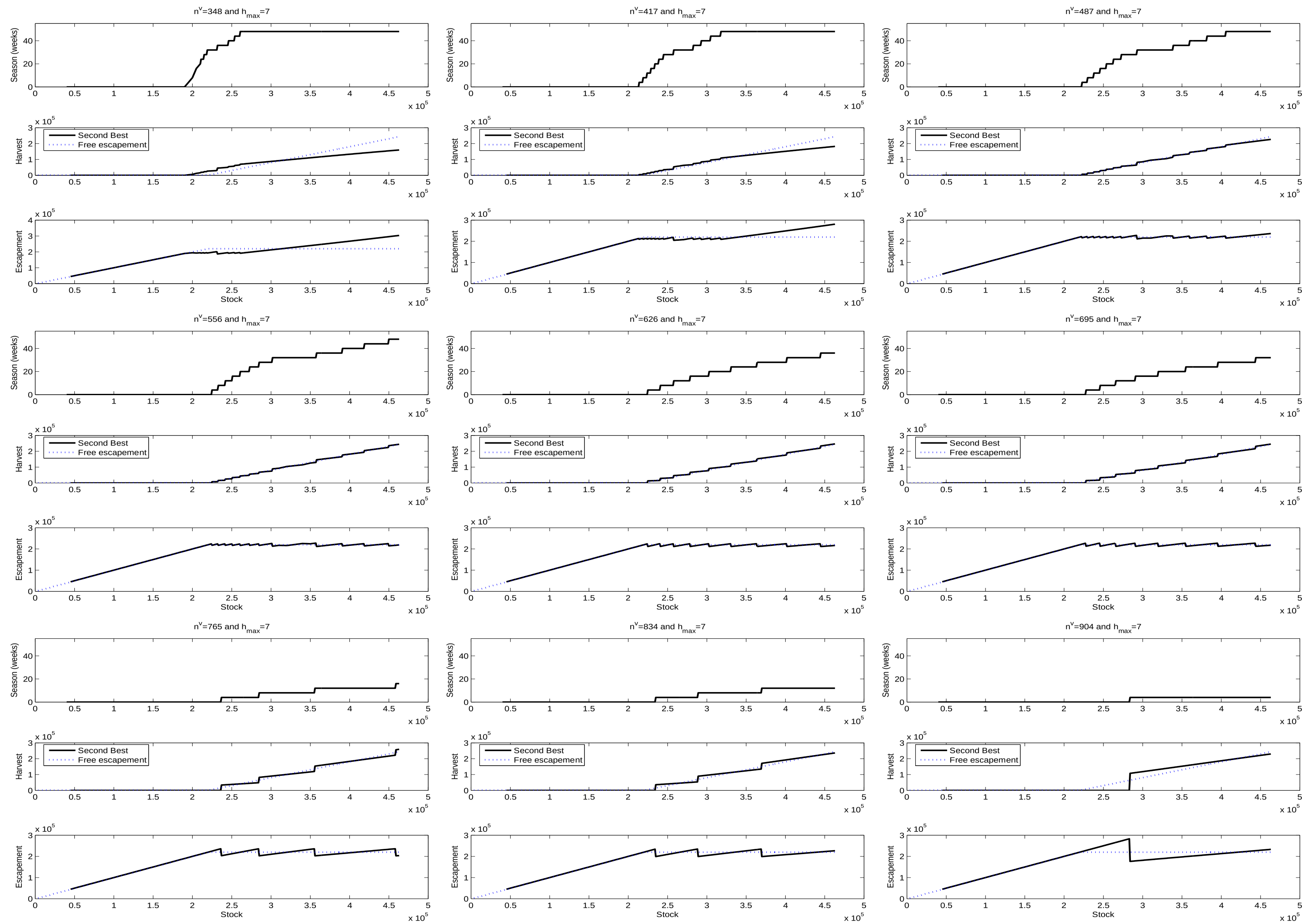

Figure 11: Slides of the $T(X_{t,1}, n^v|\overline{h} = 7)$ rule for different number of vessels.