The Optimal Management of a Natural Resource with Switching Dynamics

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Abstract

This paper analyzes the optimal management of a natural resource, such as a fishery, where the dynamics of the resource shift between different states at random times due to the effect of external forcing such as climate. This means that the parameters describing the biological relationships are different under different states. Using a classical linear control model I investigate how the switching behavior influences the optimal exploitation of the resource. The optimal switching conditions are used to identify the thresholds determining the status, opening/closing, of the fishing industry. The model is applied to the Peruvian anchoveta fishery located along the north-central coast of Peru. The optimal management policy that is constituted by four thresholds defining the stock levels at which the industry switches status under each state of the stock dynamics. Further, I show how such thresholds are influenced by the probability of a regime shift and other key parameters of the model, e.g., the maximum capacity of the fishing industry. This analysis gives important indications for the management of a natural resource with alternating dynamics, which can be used to design policies that adapt to the variability of the physical environment.

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1. Introduction

It is typical for marine ecosystems to fluctuate around some persistent trend or equilibrium. However, marine systems are occasionally exposed to transformations by means of either natural phenomena or anthropogenic interventions (or both) which may cause sudden shifts in the state of ecosystems (e.g., Scheffer et al., 2001). In the ecological literature, this is referred to as regime-switching (Lees et al., 2006). A regime shift can induce drastic drops in the abundance of a population or changes in the biological/ecological structure of communities, like changes in the growth rate. Examples include the shifting between oligotrophic and eutrophic states in lakes (Carpenter et al., 1999), the oscillation of the dominant species in oceans, e.g., anchovies and sardines in the Pacific (Chavez et al., 2003), or the collapse of fish stocks like the case of the collapse of the Georges Bank Haddock fishery (1960s-1990s) (Collie et al., 2004).

When the dynamics of a natural resource can switch between alternative stable equilibrium and once the threshold between these equilibria is crossed it may be difficult to push the system back to the original equilibrium (Carpenter et al., 1999; Scheffer et al., 2001; Peterson et al., 2003). This has implications on the management of the natural resource. In fact, the switching between equilibria could induces a hysteretic behavior of the optimal management policy (Carpenter et al., 1999; Scheffer et al., 2001).

Scientists advocate that the management of fisheries should incorporate regime switching and gain a better understanding of their determinants (e.g., Beamish et al., 2004; Collie et al., 2004; Rothschild and Shannon, 2004). Some (e.g., Polovina, 2005; King and McFarlane, 2006) have suggested the use of regime-specific harvest rates, such as with low harvest rate, or even closing the fishery, during low productivity regimes and a high rate in the high productivity regimes. Therefore, it is necessary to identify the nature of the shifts to design management strategies that adapt or mitigate the effects of the shifts (deYoung et al., 2008).

Bakun (2005, p.974) defines as regime shifts in marine ecosystems a "persistent radical shift in typical levels of abundance or productivity of multiple important components of marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent." This paper analyzes the optimal management of a fishery in which the dynamics of the fish stock shift between different states at random times. Like in (Hamilton, 1989), regime shifts in a time series are defined as "episodes across which the behavior of the series is markedly different." Considering the dynamics of a natural resource stock, this implies that the dynamics of the stock is different under the different regimes, i.e., the parameters describing the biological relationships are different under different regimes.

Using the classical linear control by Clark and Munro (1975) I investigate how regime switching stock dynamics influence the optimal extraction of the resource. I assume that any variation in the harvesting rate involves a lump-sum payment. The presence of switching costs implies that the agent may delay opening (closing) to harvest if the value of the resource is not large enough to sustaining the opening (closing) costs (e.g., Nøstbakken, 2006). When the stock switches between regimes, the harvest strategy is less clear. An important question is whether expectations toward regime shifts actually affect the way an agency manages the fishery. Since managerial decisions over the status of the resource varies in response to the state followed by the natural resource, the number of critical points on which the harvest strategy is based increases. Hence, the optimal policy involves opening/closing the resource to exploitation when the thresholds are crossed.

Despite the vast treatment of regime switching in the ecological literature, the integration of the role of regime switching behavior in the fisheries economic literature remains incomplete. Recently, (Polasky et al., 2011) developed an optimal management resource model that incorporates both a potential collapse and switching dynamics of a natural resource. Allowing for both exogenous and endogenous shits, they assume that sometime in a future period the resource will shift to an alternative regime from which it will never return. Unlike Polasky et al. (2011), in this paper the dynamic of the resource is allowed to switch back and forth between two alternative regimes at any point in time.[1]

I derive solutions of model that are used to identify the critical values, thresholds, that determine the opening/closing of the fishing industry. Using a numerical analysis, I show how such thresholds are influenced by the probability the stock will switch regime and other key parameters of the model, e.g., the drift and the variance of the stochastic process describing the natural stock. Results indicate that the thresholds defining the optimal management strategy are highly sensitive to changes in the model's parameters.

[1]The shift is first treated as exogenous, but the model will be extended to endogenous switching in its further development. In fact, the next step of this analysis involves an extension of this model which will allow switching probabilities to be endogenous, that is to depend on the stock itself and some exogenous (natural) conditions.

The article is organized as follows. The next section introduces the theoretical model of the optimal management of a natural resource with regime switching behavior. The optimal solutions are derived in section three. The illustration using data on the Peruvian anchoveta fishery, is presented in section four. The results of the numerical analysis are then presented in section five. Finally, [...]

2. The Model

Consider an exploited natural resource like a fish stock, which is denoted by x. Let assume that the transition process describing the dynamics of the resource can shift between two alternative states, which differ in the characteristics of the biological structure of the resource. In other words, the parameters defining the dynamics of the resource are different under the two states. This behavior is described by a Markov regime switching model where the parameters of the stock dynamics shift between states

$$dx_t = \mu_{s(t)}(x_t, y_t)dt + \sigma_{s(t)}(x_t)dW_t, \quad \forall x_t > 0, \tag{1}$$

where $\{s(t)\}$ is a Markov process denoting the state of the resource, y denotes the resource that is consumed, e.g., harvest in case of a fishery, and dW is an increment of a Wiener process independent of s with $dW = u_t\sqrt{dt}$, $u_t \sim N(0,1)$, such that $\mathrm{E}(u_t u_{t'}) = 0$ for $t \neq t'$, and $\mathrm{E}(dW) = 0$, $\mathrm{E}(dtdW) = 0$, $\mathrm{Var}(dW) = dt$ (Kamien and Schwartz, 1991), where E symbolizes the expectation operator and Var indicates the variance.

The two components of the process, $\mu_s(x, y)$ and $\sigma_s(x)$ are known functions that correspond to the expected drift rate and the volatility of the resource. The drift rate represents the resource growth function, which is assumed to be linear in y. The growth function and the volatility can take different values when the process s is in different state. Having a different drift term for each regime implies having different biological parameters of the population under each state. For instance, the nature of the biological relationship may be qualitatively the same, but the magnitude of growth rate or natural mortality is different under different states.

As in Guo et al. (2005), it is assumed that s is observable and that the probabilities of moving between states follows a Poisson law such that this process is a two-state Markov chain alternating between two states, i.e., $s = 1, 2$.[2] Let $\lambda_s dt$ denote the (transition) probability of leaving state s. In other words this is the probability to shift from state s to the alternative state s' in the interval time dt. Thus, a complete representation of the transition between states between time t and $t + dt$ is given by the probability matrix

$$\Lambda = \begin{bmatrix} 1 - \lambda_1 dt & \lambda_1 dt \\ \lambda_2 dt & 1 - \lambda_2 dt \end{bmatrix}.$$

The Markov chain is assumed to be irreducible such that there are no absorbing states, i.e., $0 < \lambda_s dt < 1$, $i = 1, 2$, meaning that there exists no irreversible state of the stock dynamics.[3] This implies that in each time period there is a positive probability that drift and volatility may change as a results of the regime shift.

[2]Perrings (1998) and Rothschild and Shannon (2004) suggest the use of Markov chains to model the transition between alternative regimes, or states, of an ecosystem.

[3]$1 - \lambda_s dt$ could be interpreted as the resilience of state s.

The resource is exploited by an industry that extracts rents for the society. An economic agent such as a social planner or agency that chooses the harvest policy that maximizes the present value of the future stream of rents extracted from the industry subject to the dynamics of the resource (1). The objective function of the problem is:

$$V(x,s) = \max_{0 \le y \le y_{max}} \mathrm{E}\left\{ \int_0^\infty e^{-\delta t} \left(p - c(x)\right) y \, dt \right\}, \tag{2}$$

where $V(x,s)$ denotes the current value function, $c(x)$ is the harvesting cost, y_{max} indicates the maximum feasible harvest, and δ is the discount factor. Because the stock dynamics depend on the current regime, at each instant the relevant state variables are $\{(x,s) : x \in \Re_+, s = 1,2\}$. This implies that also the value-maximizing harvesting policy depends on the state as well as the resource.

In the deterministic case, when $\mu_1 = \mu_2$ and $\sigma_1 = \sigma_2 = 0$, because the problem is linear in the control variable the optimal harvest policy follows a bang-bang approach with a constant harvest rate (Clark and Munro, 1975). When the stock is above its steady-state level, it is optimal to decrease the stock as rapidly as possible with $y = y_m ax$. Notice that it is assumed that y_{max} is large enough to drive the stock down. When the stock is below the steady-state level, it is optimal not to harvest, $y = 0$, so that the stock can be quickly rebuilt. Hence, at every point in time, the optimal harvest policy follows the maximum rapid approach path (MRAP) toward the optimal (steady-state) level (Spence and Starrett, 1975).

The optimal harvest policy involves either fishing at maximum capacity or not fishing at all. Thus, changing harvest rate involves either opening or closing the fishing industry which requires a lump-sum payment. For instance, opening the fishery entails bearing administrative costs such as for setting up enforcement/monitoring system, while closing the fishery could imply compensating the fishermen left idle. Let M_o and M_c denote opening and closing costs, respectively. The problem is still linear in the control variable and the MRAP solution is better than harvesting at a constant rate at all times (Brekke and Øksendal, 1994; Nøstbakken, 2006).

In the presence of start-up or shut-down costs the agent may delay opening to harvest if the profitability of the fishery is not large enough to sustaining the opening costs. Similarly, with positive closing costs closing the fishery may be delayed even if the stock level is lower than the steady-state level, which would induce the closure in the zero-fixed cost case. Therefore, the critical stock level that would induce a closed fishery to open exceeds the stock level that would induce an open fishery to close. Hence, similarly to the well known case of entry and exit decisions of a firm under uncertainty (e.g., Dixit, 1989), the status of the fishery (open/closed) is determined according to not just one but two critical levels of the stock.

In the model presented here, though, the dynamic of the resource stock may switch between states. This introduces another source of uncertainty that creates a richer set of strategies than the deterministic model or even for the stochastic single-regime stock with fixed costs. The presence of fixed costs and a switching dynamics creates a "double type" of hysteresis, with two critical values for each state of the resource dynamics.[4] It is worth noting

[4]In the single state case, hysteresis indicates the gap between opening and closing thresholds. In the two states case, it indicates the gap between opening, or closing, thresh-

that even in the absence of fixed costs the agent could delay or anticipate the change in the status of the industry due to the expectation of a shift in the state of the resource. For instance, given that the resource is in a less favorable state, the agent may delay stopping harvest if he anticipates that the resource will shift to a more favorable state.

To clarify, let x_s^* denote the level that triggers the opening of the fishery under state s. In each state, for stock values above this threshold the value of an open fishery weakly exceeds the value of a closed fishery plus the cost incurred by opening the industry to harvest; and the optimal harvest policy is to fish at maximum capacity. On the contrary, x_s^{**} denotes the stock level that triggers the closing of the fishery under state s, that is, below this threshold the fishery is closed. This is because the value of a closed fishery weakly exceeds the value of an open fishery plus the closing costs. In this case no harvesting occurs. In the range between the two critical points the fishery remains in its current status. If the fishery is closed, the fishery will remain closed because the agent holds an option to open, but even though opening would generate profit, this would be small enough that the agent may delay opening until conditions improve, that is when the upper threshold x_s^* is crossed (from below). The other case arises when an open fishery will remain open and harvest will be set at its maximum level until the lower threshold x_s^{**} will be crossed (from above). At that point it is optimal to shut down the industry.

The cases just described arise when each regime is considered separately. But how different is the situation if at any point in time the dynamic of

olds for the two states.

the stock can switch regime and changing harvest rate is costly? There are instances where the status of the fishery (open/closed) is the same as in the single regime case. But, there are also values of stock for which different behavior can arise. This is addressed next.

3. Solving the Regime Switching Problem

It is assumed that the two states can differ due to different growth rate of the resource so that the resource can be either in a high productive (H) or low productive state (L). In this case, there exist four regimes, indexed by R, which are {*high, closed*} and {*high, open*} when the resource is highly productive and the harvest rate equals zero or y_{max}, respectively, {*low, closed*} and {*low, open*} when the resource is less productive and the harvest rate equals zero or y_{max}, respectively, with $R = 1, \ldots, 4$.

The solution of the problem (1–2) is given by the stock thresholds defining the range of stocks for four regimes that are given by the combination of the states of the stock dynamics and two status for the fishing industry, open/closed. Thus, the solution consists of a pair of critical values for each state of the natural resource leading to existence of four regimes.

Under either state of the resource dynamics, high or low, the thresholds triggering the opening are denoted as (x_H^*, x_L^*), and those triggering the closing are (x_H^{**}, x_L^{**}). The order of the trigger points depends on the parameters of the model, mainly the switching costs and the transition probabilities. Under the assumption that the resource is more productive under state H than L, let consider the configuration where the thresholds follow the sequence:

$x_H^{**} < x_L^{**} < x_H^* < x_L^*$ (figure 3).[5] For values below x_H^{**}, regardless the state, it is optimal to keep the fishery closed at all time. The opposite is true for values above x_L^*. In that case it is optimal to keep the fishery open. For the other ranges of stock value the optimal behavior is less clear. In the range $x_H^{**} < x < x_L^{**}$, under state H an open (closed) fishery would remain open (closed). But what happens in case the stock shifts to state L? Following a shift to state L, it would be optimal to shut down the fishery because the value of a closed fishery (the value or the option to enter) exceeds the value of an open fishery plus the closing costs. For this range, in state L the fishery is closed at all time and a shift in the stock dynamics would not change the status of the fishery.

The range $x_H^* < x < x_L^*$ presents a similar situation although for reversed states. Under state L, a closed fishery would remain closed unless the stock shifts to state H, which would induce the fishery to open. When it is open, the fishery remains open no matter what is the state. Notice that under state H it is never optimal to keep the fishery closed. Finally, when the stock is in the range $x_L^* < x < K$ the fishery is always open no matter the state of the stock dynamic.

Solutions of optimal switching problems are provided by (e.g.) Brekke and Øksendal (1994), Fackler and Sengupta (2005), and Guo et al. (2005) Following Fackler and Sengupta (2005), the HJB equation associated with

[5]For example it could be possible that the maximum attainable population K is less than one of the thresholds; meaning that for high opening costs it would be best to wait until the stock reaches a very high level.

the optimization problem is the following equation:

$$\begin{aligned}\delta\, V(x,R) = \max_{0\le y\le y_{max}} \Big\{ &(p - c(x))\, y + \mu_R(x,y)\, V_x \\ &+ \frac{1}{2}\,\sigma_r^2(x)\, V_{xx} + \sum_j \lambda_{R,j}\,[V(x,j) - V(x,R) - M_{R,j}] \Big\}\end{aligned} \tag{3}$$

where $\lambda_{R,j}$ is the instantaneous probability of switching from the current regime R to regime j; notice that $1-\sum_j \lambda_{R,j}$ is the probability of remaining in regime R. As before, each change in the state requires a lump-sum payment (fixed cost) of $M_{R,j}$. The term $(p - c(x))\, y$ is the immediate profit, and the remainder of the right-hand side is the continuation value (the outcome of future optimal decisions). The last term corresponds to the expected change in the value of the fishery due to a regime shift given by the value of the resource after the switch minus the value of the resource before the switch and the cost of switching. The optimum action (harvest) maximizes the sum of these components. Thus, the present value of the fishery equals the expected stream of profits (payoffs) derived after adopting the optimal harvest policy and allowing for regime switching in the stock dynamics.

The optimal value function for the problem must satisfy the following complementarity conditions

$$\begin{aligned}\delta\, V(x,R) \ge\ &(p - c(x))\, y_{max} \times I + \mu_R(x,y)\, V_x \\ &+ \frac{1}{2}\,\sigma_R^2(x)\, V_{xx} + \sum_j \lambda_{R,j}\,[V(x,j) - V(x,R) - M_{R,j}]\end{aligned} \tag{4}$$

and

$$V(x,R) \ge V(x,j) - M_{R,j}, \quad \forall R \ne j \tag{5}$$

where I is an indicator taking value equal to 1, $I = 1$, when the industry is open under state s, $R = \{s, open\}$, and $I = 0$ otherwise. The left-hand-side of (4) is the current value of the fishery in regime R, the opportunity cost of regime R, while the right-hand-side denotes the expected change in the value of the fishery given by the instantaneous rent, $(p - c(x))\, y_{max}$, plus the value gained from changes in the stock, $\mu_R\, V_x + 1/2\, \sigma_R^2\, V_{xx}$, including the expected impact of a regime shift on the value of the resource, $\sum_j \lambda_{R,j} \left[V(x, j) - V(x, R) - M_{R,j}\right]$.[6] The second condition (5) says that the value of remaining in regime R must be greater or equal than the value that can be obtained after the switch to regime j minus the cost of switching. Notice that these conditions apply to each regime and at least one of these conditions must hold with equality for each x and R.

An alternative solution method would be to solve the model using (4) for each regime and to use the boundary conditions given by the "value matching" (5) and "smooth pasting" conditions at the switching points (e.g., figure 3) as described in Dixit and Pindyck (1994, pp.130–132) and Fackler and Sengupta (2005). At each threshold, x_s^* or x_s^{**}, such conditions hold with equality meaning that at those points the agent is indifferent between switching and not switching regime. However, with this approach it is more difficult to determine the optimal conditions when differential equations are not linear in the stock variable as in this model.

[6]To be consistent with the theory on real option, the left-hand side of (4) can be interpreted as the opportunity cost of holding the option to switch regime, which in equilibrium must equal the expected capital gain. The latter is made of the expected change in the value conditional on the current regime plus the change in value due to a regime shift weighted by the probability of a shift (Guo et al., 2005).

4. An Illustration: The case of the Peruvian Anchoveta (*Engraulis ringens*)

In this section the model is illustrated using data on the Peruvian anchoveta population located along the coast of northern and central Peru (between 4 and 14°S) where the anchoveta population is more heavily concentrated (Pauly and Tsukayama, 1987). The Peruvian anchoveta fishery started in the early 1950s and it is the largest single-species fishery in the world (Tsukayama and Palomares, 1987; Glantz, 1990). Landings are almost entirely processed into fish meal destined to feed livestock, and only recently some is processed for human consumption (Glantz, 1990; Freón et al., 2008).

The anchoveta population depends on the cold and plankton-rich upwelling waters of the Humboldt Current (HC) and it is limited in the periods when the seasonal upwelling is interrupted by the El Niño phenomena (e.g., Brainard and McLain, 1987; Chavez et al., 2003). As a result, the anchovy population is subject to considerable interannual (years) or even multidecadal variability, with swings in synchrony with sardine shocks throughout the world, but especially in the area of the HC ecosystem suggesting the presence of alternating anchovy ans sardine regimes (Lluch-Belda et al., 1989; Chavez et al., 2003; Alheit and Niquen, 2004). Moreover, there is some indication of different stock-recruitment relationships under favorable or unfavorable climatic conditions leading to conclude that anchovy's recruitment is affected by climatic anomalies in a nonlinear fashion (Cahuin et al., 2009). Given the amount of discussion on the existence of different regimes in the anchoveta population an application to a regime switching model to this particular fishery seems particularly appropriate.

As in the theoretical model, the dynamics of the anchoveta stock is modeled by a generalized Brownian motion where both drift and volatility terms depend on the stock level as well as on the current state, $dx = \mu_s(x, y)\, dt + \sigma_s(x)\, dW$, where $s = 1, 2$. Recall that the dynamic is structurally different under the two states meaning that the parameters take different values in the two states. The growth of the stock is represented by a logistic growth function and the stock is exploited by a fishing industry, that is, $\mu_s(x, y) = r_s(1 - x/K_s) - y$, where x denotes the total biomass and y is harvest.[7] The intrinsic growth rate r and the carrying capacity K of the stock are allowed to be different under each state. The volatility of the stock dynamics is assumed to grow with the stock and to be different in each state. This can be interpreted as random disturbances influencing the population and whose influence is linearly dependent to the stock level. Therefore, the dynamics of the natural population take the following form

$$dx = [r_s x(1 - x/K_s) - y]\, dt + \sigma_s\, x\, dW. \tag{6}$$

The stock dynamics of the Peruvian Anchoveta is estimated using data from Pauly et al. (1987) on estimated monthly biomass obtained from virtual population analysis (VPA) and catch for the period 1953–1981. The catch data are given by the total withdrawals of anchoveta that are obtained by multiplying nominal catch by a factor of 1.2 adding consumption by guano

[7]The logistic growth function is standard choice for pelagic fisheries and and it is used for the Peruvian anchoveta as well (e.g., Freón et al., 2008). An age-structured model would provide a more realistic representation of this population, but such a detailed model would unnecessarily complicate the analysis.

birds, bonitos and seals to account for unreported catches and natural predation (Pauly et al., 1987).

Since the data are discrete, the continuous-time diffusion process (6) is approximated by

$$\frac{x_t - x_{t-1} + y_{t-1}}{x_{t-1}} = r_s + \frac{r_s}{K_s} x_{t-1} + \varepsilon_t \tag{7}$$

where ε is normally distributed with mean zero and variance σ_s^2. This equation is estimated allowing for two potential states in the parameters of the stock dynamics using the *MS Regress* MATLAB® package provided by Perlin (2010).[8] The results show that almost all coefficients are strongly statistically significant and all have the expected sign (table **??**). The estimates provide empirical evidence for the existence of two alternative states for the stock dynamic. The intrinsic growth rate is almost nine times larger under state 1 indicating that state 1 has larger productivity than state 2. The parameter indicating the carrying capacity of the stock can be derived using the estimated ratio between the intrinsic growth rate and the carrying capacity, r_s/K_s, and the estimated growth rate r_s. The estimated carrying capacity for the high state is around 25,900 thousand tons while for the low state is around 17,400 thousand tons. The states' variances are also highly significant. Given these results, state 1 is characterized by higher growth and carrying capacity and larger variability than the alternative state. Thus,

[8] The series are not seasonally adjusted. It is documented in the literature that seasonal adjustment distorts the dating of the turning points (shifts) because it removes information relevant to the regime switching (e.g., Franses and Paap, 1999; Luginbuhl and de Vos, 2003; Matas-Mir et al., 2008). Hence using seasonally unadjusted data produces more reliable estimates of the regimes.

state 1 is denoted as the high productivity state (H) and state 2 the low productivity (L) state.

The estimate regime switching model predicts the Peruvian anchoveta stock very well (figure 4). The probability of remaining in either regimes are small indicating that both states have very small resilience and resource switches often state. Looking at the estimated (smoothed) probability for the highly productive state, it appears that the low productive state dominated throughout the sample period while the high productive state was in place mainly in the period 1959–1972 and partly in 1980–1981.

This results is supported by the existing scientific literature. There is large evidence supporting the existence of an anchovy favorable period in the interval 1950–1970 in the HCS due to the occurrence of a lasting period of low temperature anomaly (e.g., Chavez et al., 2003; Cahuin et al., 2009). Colder water temperature favours the productivity of the habitat with positive effects on the recruitment of the anchoveta population through density-dependent regulation. According to the estimates, the highly productive state was working during 1959–1972, the period of the build-up of the fishery that ended with the major collapse due to the 1972–1973 El Niño event (Alheit and Niquen, 2004). That corresponds to a period of exceptional high and variable recruitment (see Pauly et al., 1987, figure 6, p.152). Cahuin et al. (2009) also observe high recruitment rates in the 1963–1971 period, and several climatic indexes indicate a shift in the 1970s (Chavez et al., 2003). Hence, the evidence seems to support the thesis that a highly productive state in that period reflects the period of exceptional recruitment of the stock due to a period of favourable climatic condition, i.e., colder temperature.

5. Numerical Analysis

The optimal conditions (4)–(5) are used to numerically approximate the thresholds for the stock that trigger the regime shift using a Matlab procedure described in Fackler and Sengupta (2004). The parameter values used for the approximation are reported in table 2. The parameters for the carrying capacity are rescaled based on the capacity of state H. This means that the solution for the optimal thresholds will be relative to it. The maximum harvest rate, y_{max}, is set at the maximum harvest relative to the carrying capacity in state H, i.e., $y_{max} = \max{(y/K_H)}$ observed over the sample period. The maximum harvest rate is large compared to the maximum sustainable yield (MSY) for the harvest, MSY$= rK/4$, for the high state, MSY$_H = 0.047$, and low state, MSY$_L = 0.003$. Hence, fishing at maximum capacity can easily drive the stock to extinction. The values for price, cost per unit of effort, fixed costs, and the discount rate are chosen arbitrarily.

The harvest cost function is assumed to take the following form $c(x) = c/x$. The solutions need to be approximated over a carefully specified range of values for the stock. The long-run distribution of the anchoveta stock with no harvesting and under both states of the stock dynamics is derived to check the range of values that the stock can take. The distribution is obtained using the parameter values and assuming no harvest, $y_{max} = 0$. Figure 5 shows the densities for each states. As expected, the distributions are centered around their respective carrying capacity. According to the long-run distributions, the interval $[0, 2]$ covers all possible stock realizations. Thus, the state space for the stock of Peruvian anchoveta used in finding the solutions is defined by 1000 points in the $[0, 2]$ interval.

Given the parameters of the model the optimal thresholds for the management of the Peruvian anchoveta fishery are the following. When the resource is in its low productivity state it is optimal to open the industry and to harvest at maximum capacity once the stock level crosses the level of 0.4802 from below, x_L^*. This is relative to K_H. Note that this is higher than the carrying capacity of the low state.[9] Instead, it is optimal to shut-down the fishery once the 0.2997 stock level, x_L^{**}, is crossed from above. The thresholds for the optimal harvest policy under the high productivity state are both lower than those under the less productive state. The opening threshold, x_H^*, is at 0.4722 and the closing, x_H^{**}, at 0.2957. This looks reasonable given that since the stock is more productive it can sustain some larger pressure. That is, it is optimal to anticipate the opening and delay the closing of the industry than in the case when the stock is less productive because it can rebound more rapidly.

The thresholds determining the optimal harvest strategy for the Peruvian anchoveta depend on the parameter of the model. To evaluate qualitatively the impact of the model's parameters on the harvest policy a number of simulation results are performed. Increasing the probability to switch from the low to the high state means increasing the likelihood that in the next period the stock will be more productive than in the current period. As

[9]It is possible that the carrying capacity is less than one of the switch points. For instance, this could occur if the cost of opening the fishery is high then it would be optimal to wait until the stock level is very high.

a consequence, given the fact that the switching dynamic is an exogenous event, we may expect that the agent will increase the exploitation of the resource even while being in the less productive state. Figure 6 shows the opening and closing thresholds for both states. The stars indicate the optimal solutions derived for the parameter of table 2. Both thresholds for the low regime show a slight decrease as a result of the increasing expectation of high natural productivity. This means that it would be optimal to anticipate the opening of the industry, i.e., start fishing at lower population levels, and to delay the closing, by driving the stock level to lower levels. The opposite should apply when the stock is currently experiencing high productivity and there is an increasing likelihood of switching to a less productive dynamic. Figure 7 shows that the closing threshold for the high state increases until the probability of switching to a low regime gets to 0.1 and the remains stable thereafter. This indicates that when the expectation of a low state is very low, i.e., less than 10 percent, it would be optimal to anticipate the closing of the stock to exploitation.

Figures 8 and 9 illustrate the impact of varying the volatility of the stock under the two states on the opening and closing thresholds. Increasing volatility means increasing the uncertainty of the stock dynamics. This simulations show that when the dynamic of stock becomes more noisy and hence more uncertain the difference between the optimal thresholds of the low productive regime increases. Specifically, the opening threshold increases with uncertainty, while the closing threshold decreases. This means that it is optimal to delay the opening (closing) of the industry because the option of waiting to open (close) has more value when uncertainty is higher.

The thresholds for the high productive regime appears to be insensitive to the uncertainty of a low productive resource. The difference between the optimal thresholds of the high productive regime also increases in a similar fashion. Thus it appears that under both states of the dynamics it is optimal to maintain the current status of the industry until uncertainty resolves than paying the switching costs, as pointed out for the single state case analyzed by Nøstbakken (2006). Interestingly, the hysteresis due to the presence of alternative dynamics becomes larger with uncertainty.

The simulations show that when industry capacity increases it is optimal to start fishing at smaller stock levels and stop fishing at higher stock levels (figure 10). This indicates that the option of waiting to open (close) becomes less valuable as the capacity of the industry increases. The maximum capacity indicates the maximum harvest rate of the fishing industry. The capacity can be increased by allowing more fishermen into the industry or allowing existing fishermen to increase their input levels. The hysteresis due to the alternative states of the stock dynamic decreases as the capacity increases.[10] The thresholds tend to converge meaning that the optimal policy would not be different for different stock dynamics.[11] Therefore, if the capacity of the industry increases, the management agency should intervene by reducing/increasing the stock levels at which the stock can start/stop being exploited.

As expected, increasing the fixed opening costs delays the opening to

[10] Specific plots can be provided.

[11] These results are consistent with Nøstbakken (2006) where, at low output price, switching curves on the price–stock space move outwards as capacity increases and they do so in a less than proportional fashion.

fishing (figure 11). In this situation, it is more profitable for the agent to maintain the status of the industry for a while until the situation improves, then the fishery can be opened. The closing thresholds decreases as a result of higher opening costs. This indirect effect are similar to what observed by Mason (2001) for mines. When opening becomes more expensive, the agency that closes the industry will be less willing to reopen, which would reduce the value of the option to open. Also, the increase of closing costs delays the closing of the fishery and would induce the agency to become more conservative in opening the mine (figure 12). Interestingly, the hysteresis becomes larger at the fixed costs increase. The gap induced by the alternative resource states is small at low start-up/closing costs and it gets reversed (thresholds cross) and increases for higher fixed costs.

6. Forthcoming Analysis

In this section I extend the model to the case of endogenous switching. Endogenous switching means that the transitional probabilities are set to be explicit functions of the stock itself plus some exogenous factors that also influence the probability of shifting the state of the stock dynamics, i.e., $\lambda_{R,j}(x, z)$, where z are the exogenous factors.

One implication for restricting to exogenous switching is that the agency only reacts to the new biological conditions. Instead, allowing for endogenous regime switching the agency may influence the likelihood of changing state by adjusting its management policy. This raises a richer set of implications for the management policy of the resource.

[...]

7. Conclusions

[...]

Table 1: MS regression model

Variable	Coefficient	(Std. Err.)	
r_1	0.1896	(0.0161)	***
r_2	0.0210	(0.0089)	**
r_1/k_1	-7.33e-6	(1.38e-06)	***
r_2/k_2	-1.21e-6	(1.14e-06)	
σ_1^2	0.0035	(0.0009)	***
σ_2^2	0.0026	(0.0005)	***
λ_1	0.13	(0.02)	**
$1 - \lambda_1$	0.87	(0.08)	***
λ_2	0.08	(0.03)	**
$1 - \lambda_2$	0.92	(0.08)	***
log likelihood	286.268		
$N.obs$	347		

Note: Double asterisks (**), and triple asterisks (***) denote significance at 5%, and 1% levels.

Table 2: Parameter values

Param.	Value	Description
r_H	0.1896	Growth rate High
r_L	0.0210	Growth rate Low
K_H	1	Carrying capacity High
K_L	0.67	Carrying capacity Low
σ_H	0.0588	Stock volatility
σ_L	0.0510	Stock volatility
λ_H	0.08	Prob. to shift to High
λ_L	0.13	Prob. to shift to Low
y_{max}	0.1108	Industry capacity
p	1	Price
c	0.3	Cost per unit of effort
M_o	0.01	Cost of opening
M_c	0.01	Cost of closing
ρ	0.1	Discount rate

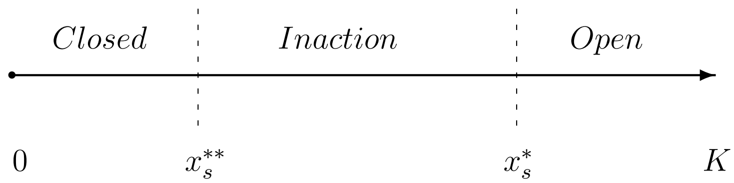


Figure 1: Thresholds under state s (K indicates the maximum attainable stock)

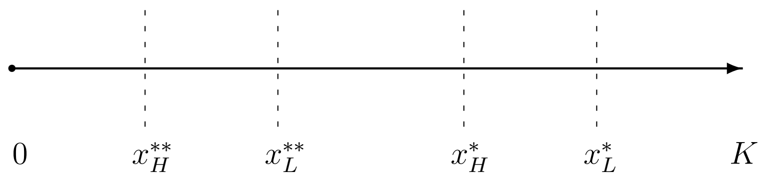


Figure 2: Thresholds (K indicates the maximum attainable stock)

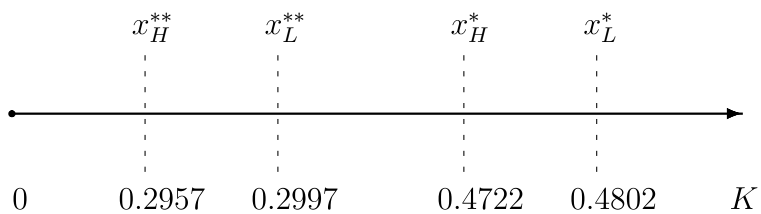


Figure 3: Thresholds (K indicates the maximum attainable stock)

Figure 4: Peruvian Anchoveta

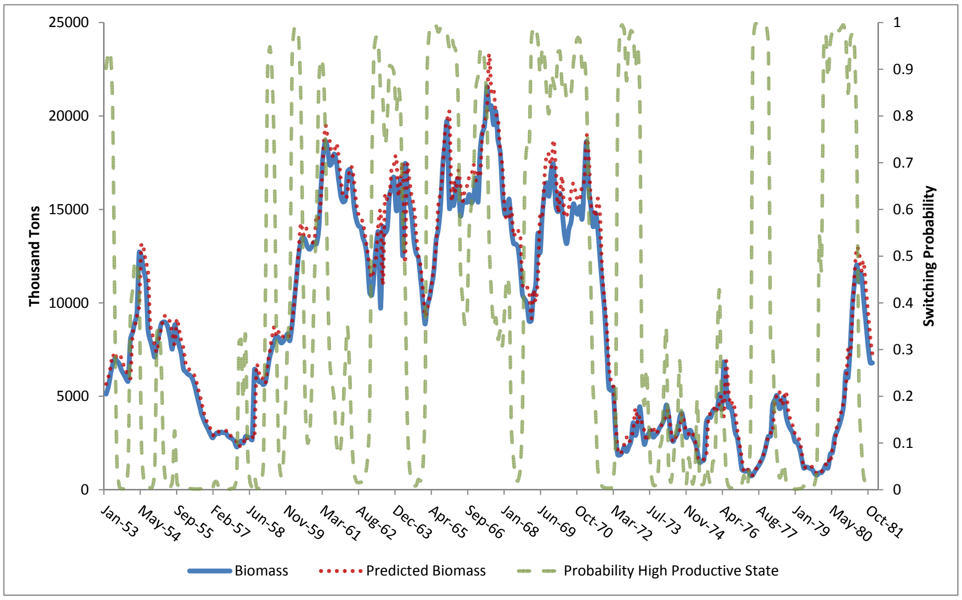


Figure 5: Long-run stock density

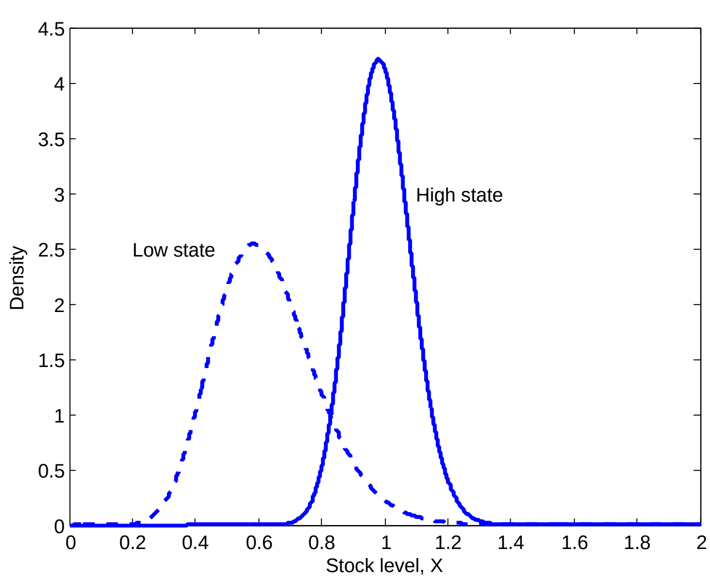


Figure 6: The impact of λ_H on the opening thresholds

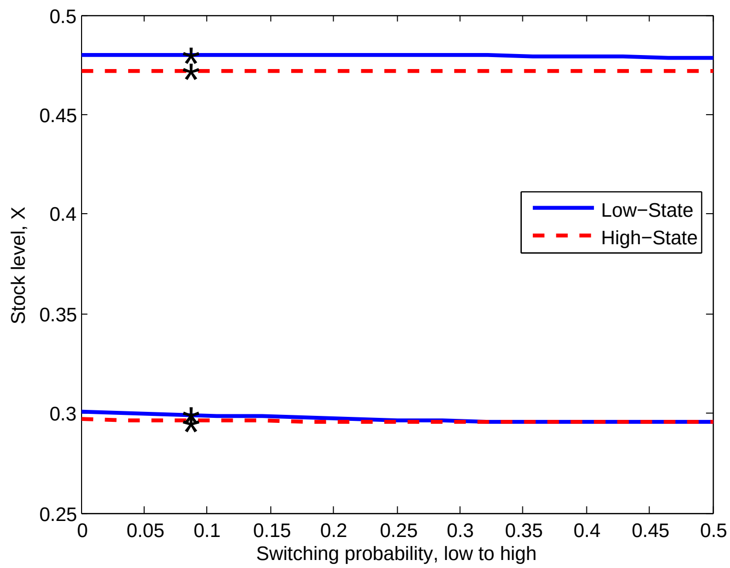


Figure 7: The impact of λ_L on the closing thresholds

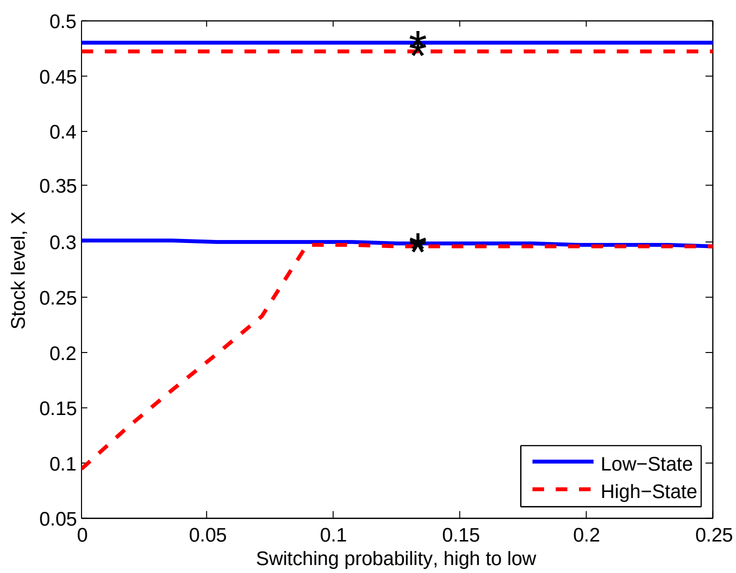


Figure 8: The impact of σ_L on the optimal thresholds

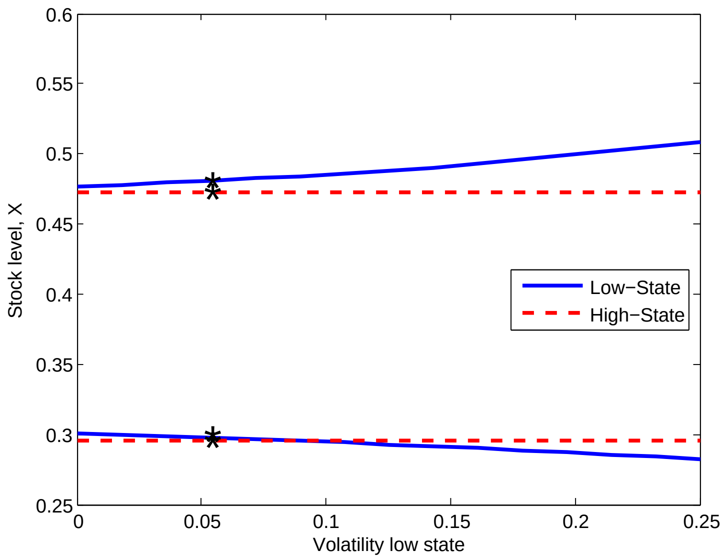


Figure 9: The impact of σ_H on the optimal thresholds

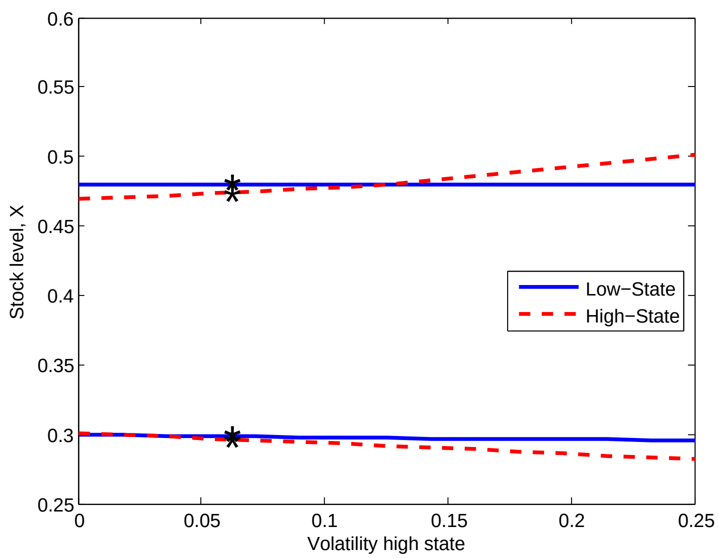


Figure 10: The impact of the maximum capacity on the optimal thresholds

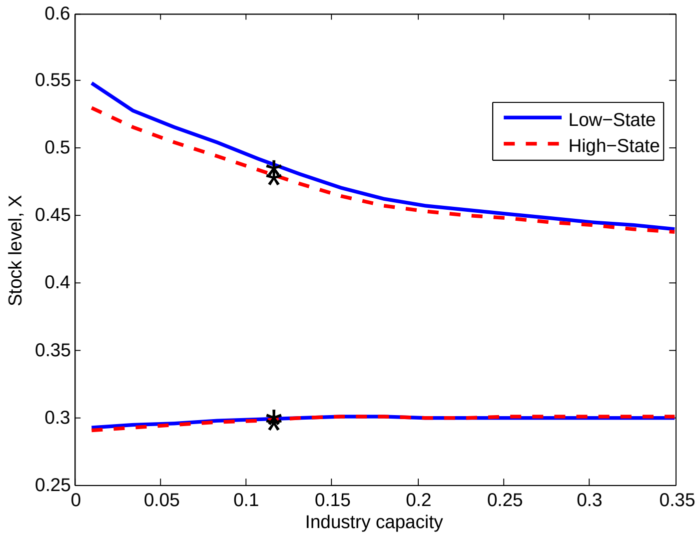


Figure 11: The impact of the opening fixed cost on the opening thresholds

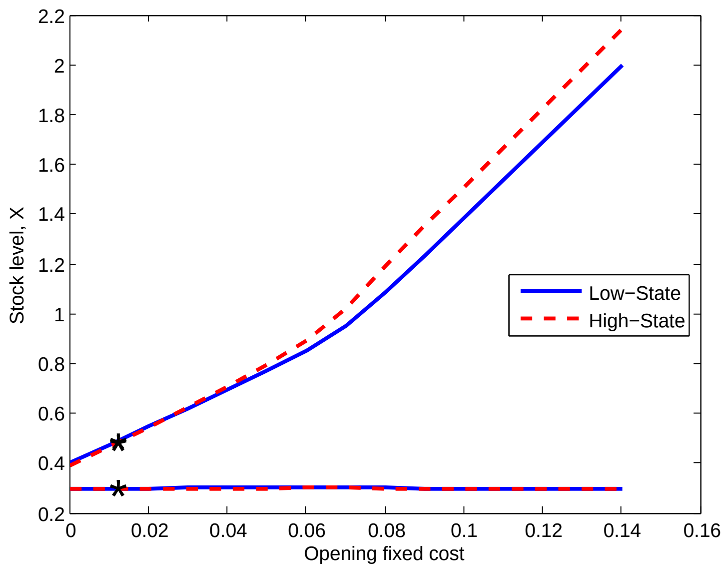
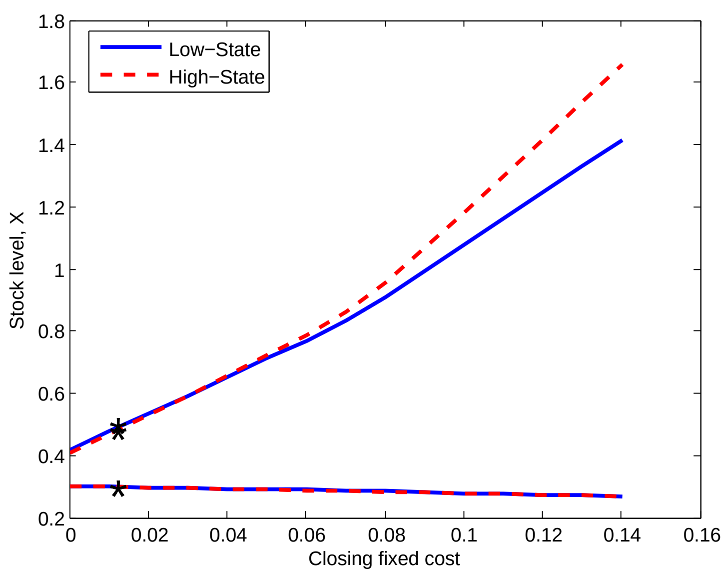


Figure 12: The impact of the closing fixed cost on the closing thresholds



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