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Regime Shifts and Resilience in Fisheries Management: A Case Study of the Argentinean Hake fishery

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Abstract We investigate the role of potential regime shifts in Argentinean hake fishery and the inter-linkage between ecological and economic resilience. We develop a theoretical model incorporated with the hazard function for resource management under alternative conditions, and derive the corrective tax. Applying the model to the case of Argentinean hake fishery, we obtain insights for fishery management in the presence of risk for a regime shift. Based on three value functions, our model simulation indicates that the higher the relative loss from the fishery collapse, the more important the risk management would be with the resilience value taken into account. A higher level of fish stock leads to a higher optimized value and a lower corrective tax rate. When the stock level is lower, we need to introduce a higher tax rate to best avoid the fishery collapse. Decomposing the marginal value of the fish stock into a stock service value for fish production and a resilience value for flip risk reduction, we find that a higher fish stock leads to a lower tax rate because of the higher resilience of the fish stock, and hence the corrective tax rate as an instrument for managing fishery becomes less important.

Keywords Regime shifts · Resilience · Corrective tax · Marine ecosystems · Argentinean hake fishery (*Merluccius hubbsi*)

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1 Introduction

Marine ecosystems play a crucial role in supporting economic prosperity and social welfare in the adjacent human communities Costanza et al. (2014). However, coastal areas and their ecosystems are subject to an increasing number of competing and conflicting activities as the world's population continues to grow (Folke et al. 2011). The impacts of human activities are altering the structure and functioning of ecosystems, thus reducing ecosystems' capacity to generate ecosystem services (MEA 2005) and crossing planetary boundaries which can put at risk the welfare of the human being (Steffen et al. 2015).

These outcomes result from a long-standing approach to managing marine ecosystems based on a flawed conceptual model that consists on the narrowly defined "optimal" harvesting of targeted stocks in systems that are assumed to be stable (Hughes et al. 2005). An emerging approach in favor of management practices that recognize coupled social-ecological systems is characterized by complex, non-linear and dynamic thresholds and inherent uncertainties (Scheffer and Carpenter 2003).

By this approach, thresholds play a key role in identifying critical points (Crépin et al. 2011). Thresholds are defined as the critical levels of one or more drivers or state variables that, when crossed, trigger abrupt changes (i.e. regime shifts) in the system (Hughes et al. 2005). In the same way but with different meaning and implications, a tipping point is a threshold for transformation from an old to a new system controlled by different critical slow variables and feedbacks (Chapin et al. 2009). When resilience has been eroded, a disturbance that previously shook and revitalized the resilient system, might now push the fragile system over a threshold into an alternative state with a new trajectory of change (Chapin et al. 2009a). In some cases, crossing the threshold brings about a sudden, large, and dramatic change in the responding state variables (Folke et al. 2011).

In this paper we model the hazard of potential regime shifts for the Argentinean hake (*Merluccius hubbsi*) fishery. We consider a representative resource manager in an optimal control theory setting to explore the implications of ignoring the risk of fishery collapse and the corrective taxes for harvests. Our model bears certain resemblance to Pindyck (1984) with an essential difference in that the loss-in-value is caused by the potential fishery collapse rather than the risk aversion loss from stock uncertainty. Under the ideal situation with perfect surveillance and compliance of the fishermen, we analyze the value of the biological stock for consumption and resilience services.

The objective of this paper is twofold. First, we explore the interlinkage between ecological and economic resilience in industrial fisheries in developing countries; and next we investigate the role of potential regime shifts in the Argentinean hake fishery. The remaining part of the paper is structured as follows. Section 2 presents the main biological characteristics of the Agentinean hake fishery. Section 3 outlines the theoretical model incorporated with the hazard function and derives the Hamilton-Jacobian-Bellman equations for resource management under alternative conditions, i.e. with and without taking into account the risk of regime shifts. We also derive formulas for the corrective tax and the value of resilience services from the model. Section 4 describes the data on the biological growth as well as the economic data on demands and harvest costs, and estimates the model parameters for numerical optimization process. Section 5 presents our simulation results based on the key model parameters and perform sensitivity analyses from uncertain parameters. Optimal and suboptimal value functions are derived and the marginal stock value decomposed into consumption value and resilience services. In Sect. 6, we sum up the study.

2 The Argentinean Hake (*Merluccius hubbsi*) Fishery

The Argentinean continental shelf extends for 769, 400 km^2, its EEZ surface is 1,164,500 km^2 and the length of its coastline is 4725 km (FAO 2014), with an extension reaching 640 km in the Falkland (Malvinas) Islands and ending to the east with a steep slope that starts at 180 meter deep (Boltovsky 1981).

The Argentinean hake is a demersal and benthopelagic species distributed along the continental shelf off Argentina and Uruguay, occasionally reaching Brazilian waters (Aubone et al. 2000). The Argentinean hake fishery is one of the most relevant demersal fishery in Latin America (Villasante and Österblom 2015). Due to its abundance, broad distribution, and scale of landings, the fishery sector is a driver for development in Argentina (Villasante et al. 2014). The fishery sector includes around 50 % of Argentinean fishing vessels, more than 10,000 direct jobs, and 40 % of fisheries exports in recent years (Villasante et al. 2016).

During the period of high exploitation between 1987 and 1997, landings of Argentinean the hake fishery (including both Northern and Southern 41 ° S stocks) increased from 435,000 to 645,000 tonnes (Dato et al. 2006). In response to the growing risks of collapse, the Federal Fisheries Council reduced the total allowable catch to 189,000 tonnes in 1999, compared to 298,000 tonnes in the previous year, which leads to the decline of total biomass and landings. At the same time, there has been an increase in discards, mainly juveniles (between 11 and 24 % of total landings during the period 1990–1997) (Dato et al. 2006), which represents economic losses of 11–77 million US$ (Villasante et al. 2014). Recent analysis of the Argentine hake fishery suggest that total removals (including reported catches, discards and illegal, unreported and unregulated catches) from Argentinean waters are 50 % higher than reported catches (Villasante et al. 2016). This phenomenon is putting at risk the sustainability and resilience of the fishery. In fact, the latest evidence indicates that stocks of the fishery are declining over time (Irusta 2015; Santos and Villarino 2015), in particular the total and reproductive biomass of the Northern stock that diminished 80 % in the period 1984–2014 (Irusta 2015).

3 The Model

In this section, we develop a model of fishery management by taking into account the risk of fishery collapse[1] due to fish stock changes. We distinguish three value functions: ideal, optimal and non-optimal value functions. The ideal value is the one where there is no risk of fishery collapse. The optimal value is the one where we take into account the risk of flips in fishery, and the non-optimal value is the one ignoring the risk of fishery flips. With these value functions, we will be able to characterize the loss caused by the risk of flips and the loss due to non-optimal management.

Let $x(t)$ be the stock of the hake population at time t, and $\tilde{x}$ some threshold stock level below which a fishery collapse would occur. As long as the actual stock is greater than the threshold level, the stock dynamics is assumed to follow the standard logistic growth function,

$$\dot{x}(t) = f(x(t)) - q(t) = rx(t)\left(1 - \frac{x(t)}{K}\right) - q(t), \, with \, x(0) = x_0 \tag{1}$$

where r and K are the instrinsic growth rate and the carrying capacity, respectively, and $q(t)$ denotes the harvest rate at time t (the dot above x denotes time derivative). Initially, we have

1 In this paper, we use the three terms regime shifts of fishery, fishery collapse and fishery flips interchangeably.

a normal regime. As time goes, however, there is always a risk for the actual stock to cross the threshold level with $x < \tilde{x}$ such that the growth process may undergo abrupt changes in the parameter values, which may result in substantial economic losses (cf. Polasky et al. 2011; de Zeeuw 2014).

Let $p(q)$ be the inverse demand function, which takes a functional form $p(q) = aq^{-b}$ for $a, b > 0$, with price elasticity of demand, b^{-1}. Then, the net social surplus can be expressed as $B(q) = \int_0^q p(q)\,dq - cq$, or more explicitly $B(q) = \frac{a}{1-b}q^{1-b} - cq$, where c is the unit harvest cost. We impose $0 < b < 1$, since the social inputs would be infinite if b is equal or greater than 1 with an inelastic demand. If the stock would always be greater than its threshold such that the stock dynamics equation (1) holds, we can express the present value of social surplus from the stream of future harvest $q(t)$, $t \geq 0$, as

$$J(x_0) = \int_0^{\infty} B(q(t)) \exp(-\rho t)\,dt, \tag{2}$$

where ρ is the discount rate.

As time goes, there is a probability for the fish stock to go below its threshold level causing a regime shift. This may reduce the future value of stocks through different channels such as an abrupt downward jump in the carry capacity and/or the intrinsic growth rate (Polasky et al. 2011; de Zeeuw 2014). Suppose that a regime shift occurs at a known date $T > 0$, then, the post-event value function becomes

$$\phi(x(T)) = \int_T^{\infty} B(\bar{q}(t)) \exp(-\rho(t-T))\,dt \tag{3}$$

where $\bar{q}(t)$ represents the best management practice for $t \geq T$, conditional on the "initial" stock $x(T)$ but a disturbed and less desirable dynamic process with lower intrinsic growth rate and carrying capacity. Facing the risk of a future flip, the decision-maker is assumed to maximize the expected present value at time 0 with respect to $q(t)$ over the pre-event period $[0, T]$, i.e.

$$V(x_0) = E_T\left\{\int_0^T B(q(t)) \exp(-\rho t)\,dt + \phi(x(T)) \exp(-\rho T)\,dt\right\} \tag{4}$$

where the expectation operator is taken with respect to the stochastic flip date T. While the first term in the curved brackets represents the present value of the stream of social surplus over the period of the normal regime, the second term is the present value of the "scrap" value at the start of the post regime-shift period.

Following Cropper (1976), Clarke and Reed (1994), Tsur and Zemel (2004, 2006) and Maler and Li (2010), among others, we can use the integration-by-parts formula to re-express the objective function in (4) as

$$V(x_0) = \int_0^{\infty} S(t)\left[B(q(t)) + \lambda(x(t))\,\phi(x(t))\right] exp(-\rho t)\,dt \tag{5}$$

where $\lambda(x(t))$ is the hazard rate for a given stock $x(t)$ at time t, and $S(t) = \exp\left[-\int_0^t \lambda(x(s))\,ds\right]$ is the survival probability up to time $t \geq 0$, with $S(0) = 1$. Since the survival function is an exponential function, as known in the literature, it is also possible to merge it with the original discount factor to arrive at an effective discount factor $\exp\left[-\int_0^t (\rho + \lambda(x(s)))\,ds\right]$. Note that the expression in (5) is the present value of the expected stream of social surpluses over an infinite time horizon, in contrast to the expected sum of the benefits from the normal and post-event present values.

The present value function, conditional upon survival at time $t > 0$, with a stock $x(t)$, can be written as

$$W(x(t)) = \int_t^{\infty} \frac{S(s)}{S(t)} \left[B(q(s)) + \lambda(x(s))\,\phi(x(s))\right] \exp(-\rho(s-t))\,ds \tag{6}$$

which is time-autonomous since the time horizon is infinite and the harzard rate function is not explicitly dependent on time.

In this paper, for convenience, we work directly on the hazard of fishery collapse (and hence the conditional probabilities over time) rather than the density functions defined on the threshold stock level. In particular, we adopt the following functional form

$$\lambda(x(t)) = -\frac{dS(t)/dt}{S(t)} = -\ln\left[1 - exp\left(-\frac{x^2(t)}{2\sigma^2}\right)\right] \tag{7}$$

where $\sigma > 0$ is a scale parameter measuring the degree of uncertainty in the threshold stock. It can be readily shown that the hazard rate function satisfies the properties $\lambda(0) = \infty$, $\lambda'(x) < 0$ and $\lambda(\infty) = 0$. At a zero stock level, the hazard rate is infinite i.e. the regime would shift immediately, whereas when the stock level would be infinitely large, the hazard rate would be zero meaning that it is completely resilient and thus safe. In practice, however, the fish stock is finite and constrained by the carry capacity with a positive hazard rate, and thus there is no stock level that is completely safe.

The decision-maker is assumed to optimize the stream of harvests, and the Bellman equation over the pre-event period can be expressed as (with the time argument suppressed):

$$0 = \max_q \left[B(q) - \lambda(x)(W(x) - \phi(x)) - \rho W(x) + W_x(x)(f(x) - q)\right] \tag{8}$$

where $f(x)$ denotes the logistic growth equation with normal growth parameters as in (1). The first-order optimality condition becomes

$$B'(q) = W_x(x) \tag{9}$$

i.e. the marginal social surplus per unit of harvest equals the shadow price of the fish stock. Using the inverse demand function, $p(q) = aq^{-b}$, together with (8), we can derive the feedback harvest rule as

$$q(W_x) = \left(\frac{a}{c + W_x}\right)^{\frac{1}{b}} \tag{10}$$

which indicates that the larger a unit of fish stock is valued, the smaller amount would be harvested for immediate consumption. The potential value for future consumption would be higher if the unit is left for growth. Together with the hazard function in (7) and the Bellman equation in (8), this rule leads to the following first-order nonlinear differential equation:

$$\begin{aligned}\rho W(x) = {} & \frac{a}{1-b}(q(W_x))^{(1-b)} - cq(W_x) - \lambda(x)(W(x) - \phi(x)) \\ & + W_x(x)(f(x) - q(W_x))\end{aligned} \tag{11}$$

As compared to Pindyck [1984, equation (14)], we have an expected concurrent loss term $\lambda(x)(W(x) - \phi(x))$ caused by the risk of a regime shift rather than the risk-aversion loss from stock uncertainty. Conditional on survival today, the flip probability over an infinitesimal period dt is $\lambda(x)\,dt$ and if a flip occurs, the loss would be $W(x) - \phi(x)$ i.e. the difference in the capitalized value based on the two different regimes. Following Weitzman (2003), the sum of the other terms on the right-hand side of (11) can be interpreted as the stationary equivalent of future social surplus, under the ideal normal regime condition with no flip risk. Together with this loss term, the whole expression represents the risk-adjusted constant equivalent value of future social surplus (cf Tsur and Zemel 2006). In other words, the present discounted value of the realized future social surplus is exactly equal to the present value of a hypothetical constant flow of benefit given by (11).

By solving the differential equation (11) for the value function $W(x)$, we can determine the feedback harvest decision rule according to (10), and characterize the optimal time path for the harvest and stock variables using equation (1), i.e. $(q^*(s), x^*(s))$, for $s \geq t$. With the total functional value with a stock level x given by

$$W^*(x) = \int_t^{\infty} \frac{S(s)}{S(t)} \left[B\left(q^*(s)\right) + \lambda\left(x^*(s)\right) \phi\left(x^*(s)\right) \right] exp\left(-\rho\left(\mathrm{s}-\mathrm{t}\right)\right) ds \tag{12}$$

The marginal stock value can be derived to be

$$\begin{aligned} \frac{\partial W^*(x)}{\partial x} &= \int_t^{\infty} \left[\frac{S(s)}{S(t)} \left(B'(q) \frac{\partial q^*(s)}{\partial x} + \lambda\left(x^*(s)\right) \phi'\left(x^*(s)\right) \frac{\partial x^*(s)}{\partial x} \right) \right] D(s,t)\, ds \\ &+ \int_t^{\infty} \frac{1}{S(t)} \left[\frac{\partial S(s)}{\partial x} B\left(q^*(s)\right) + \frac{\partial \theta(s)}{\partial x} \phi\left(x^*(t)\right) \right] D(s,t)\, ds \end{aligned} \tag{13}$$

where $D(s,t) = exp(-\rho(s-t))$ is the discount factor and $\theta(s) = S(s)\lambda(x(s))$ is the probability density with respect to flip time s. Note that the first integral in (13) represents the contribution of an extra unit of the resource to stock services for fish production (i.e. the scarcity value), and the second integral can be interpreted as the resilience value of the stock for reducing the risk of future regime shifts.

In addition to the *optimal value function* $W^*(x)$ in (12), we are also interested in two other value functions as defined below. First, we consider the ideal case without any risk of regime shifts. Then, the decision-maker would maximize the ideal objective function (2) subject to the stock dynamics Eq. (1) under the normal growth parameter values. By denoting the optimal solution to this hypothetical problem with $(\tilde{q}(s), \tilde{x}(s))$, we define the *ideal value function,* for any given stock x at time t, as $\tilde{W}(x) = \int_t^{\infty} B(\tilde{q}(s))\, exp(-\rho(s-t))\, ds$. Technically, the *ideal value function* $\tilde{W}(x)$ can be found by solving the differential equation in (11) by ignoring the expected loss term $\lambda(x)(W(x) - \phi(x))$. In the presence of fishery collapse risks, however, the solution $(\tilde{q}(s), \tilde{x}(s))$ is obviously not optimal since the risks are ignored in the optimization process. Then, we define the *non-optimal value function* as

$$W^0(x) = \int_t^{\infty} \frac{\tilde{S}(s)}{\tilde{S}(t)} \left[B(\tilde{q}(s)) + \lambda(\tilde{x}(s)) \phi(\tilde{x}(s)) \right] \exp(-\rho(s-t))\, ds \tag{14}$$

i.e. the value of the objective functional (6) evaluated along the "wrong" solution $(\tilde{q}(s), \tilde{x}(s))$ derived from completely ignoring the risks of regime shifts. As compared to the case with optimal solution, the survival probability $\tilde{S}(s)$ for $s > t$ is expected to be smaller.

By using the three different value functions, *the ideal value function*, *the optimal value function* and *the non-optimal value function*, we will be able to characterize the welfare loss caused by the risks of fishery collapse and to determine the corrective taxes (cf. Arrow et al. 2004). The corrective tax per unit of harvest can be readily derived as

$$\tau(x) = W_x^*(x) - \tilde{W}_x(x) \tag{15}$$

i.e. the deviation between the marginal stock values based on the optimal and the ideal value functions with $W_x^*(x) = \partial W^*(x)/\partial x$ and $\tilde{W}_x(x) = \partial \tilde{W}(x)/\partial x$, respectively. Without taking into account the risk of regime shifts, i.e. by ignoring the resilience service value of the stock, the resulting marginal value $\tilde{W}_x(x)$ is smaller than the optimal one $W_x^*(x)$, and therefore the corrective tax should be positive.

4 Data and Model Parameter Estimates

As discussed above, if the Hake stock undergoes some threshold level, the fishery collapse would be unavoidable with serious economic losses associated. In this section, we estimate the bio-economic model using time series data on fish stock, catch, price and cost in order to examine the optimal harvest strategy and the economic losses caused by neglecting the risk of regime shifts.

The time series data for both stocks and landings as well as the price and consumption of the Argentinean hake originate from Irusta and D'Atri (2009) and Renzi et al. (2009) covering the period from year 1986 to 2007.

Using the stock and catch data, we have estimated the logistic growth function as

$$f(x) = 0.8806x\left(1 - \frac{x}{2.1736}\right) \tag{16}$$

where $\boldsymbol{x}$ denotes the total stock of the Argentinean hake and $\boldsymbol{f}(\boldsymbol{x})$ the annual growth both in million tonnes. The estimated carrying capacity is 2.1736 million tonnes, at which the net growth rate would be zero even without human harvests since the regeneration and mortality rate are balanced at such a stock level. Note that in our dataset, the stock value ranges from about 0.49 to 1.96 million tones, outside of which we do not have any observations. What happens when the stock is below 0.49 is not known with certainty, but scientific evidence and earlier experience in fisheries management indicate that if some critical level is crossed, the fisheries may collapse with serious economic losses (Da Rocha et al. 2012).

In this paper, we consider the threshold stock to be stochastic due to exogenous shocks, which is different from the endogenous threshold problem (Tsur and Zemel 2004). Even if it is safe today and the fish stock is non-declining, there is still a risk that a regime shift would occur tomorrow due to stochastic shocks. In the scientific community, there has been no consensus on how to determine the threshold level. Following Myers et al. (1997), a reference biomass of 20 % of the virgin biomass (i.e. the carrying capacity) is a commonly used biological threshold. In this study with an estimated carrying capacity being 2.1736 million tonnes, this threshold becomes $2.1736 \cdot 0.2 \approx 0.4347$ million tonnes, somewhat below the lowest hake stock level available in our dataset. However, the threshold defined as such does not mean that crossing it would lead to an immediate regime shift[2]. When the fish stock is below such a level, it is the mean recruitment per unit of the stock that is expected to be lower than in the normal case. This means that it is possible for a regime shift to occur even if the stock is above 0.4347 million tonnes and it is not for sure that a regime shift would occur when the actual stock is below that level. To calibrate our model, we assume that the probability of a regime shift over a year, evaluated at the biological threshold according to the 20 % rule, to be the usual statistical significance level of 5 %. Then, by solving the hazard rate equation $\lambda(0.4347) = -\ln\left(1 - exp\left(-\frac{0.4347^2}{2\sigma^2}\right)\right) = 0.05$, we obtain the scale parameter to be about $\sigma = 0.1776$.

The demand function is estimated using the price and catch data (Renzi et al. 2009) according to $p(q) = \exp(6.6262)\, q^{-0.1646}$. *The* unit cost of harvesting the fish is on average

[2] The difficulty of setting such a reference level is a general problem not limited to this particular study. See Cai et al. (2012) on climate thresholds.

Table 1 A description of the basic model parameters

Parameter	Value	Description
a	630	A demand function parameter
b	0.1646	Demand elasticity (−1/b)
c	404	Harvest cost in US$ per tonne
τ	0.8806	The intrinsic growth rate
K	2.1736	The carrying capacity in million tonnes
ρ	0.10	The annual discount rate
β	0.30	The relative value loss of fishery collapse
σ	0.1776	The scale parameter on threshold uncertainty

$c = 404$ US dollars per tonne. To apply the model outlined in the previous section, we also need to specify the other economic parameters. To start with, we consider the annual discount rate to be $\rho = 10\,\%$, and assess the post-event value function to be $\phi(x) = (1-\beta)\,W(x)$ with $\beta = 0.3$ (i.e. the present value of the same fish stock in the disturbed regime corresponds to only 70 % of the value in the normal regime). We attribute the loss here to possible reductions both in the carrying capacity and the intrinsic growth rate of the fish stock (cf. Polasky et al. 2011; de Zeeuw 2014). For simplicity, however, we directly specify the loss in the value function rather than deriving it from the assumed shift in the underlying parameters since the technical details as such are not the main focus of this paper. We will analyze the fishery management problem using the parameter values in Table 1, and then conduct sensitivity analyses for other parameter values.

5 Optimization and Simulation Results

To solve the optimization problem, we apply a modified version of the stochastic control module*Scsolve* in the Matlab Toolbox*CompEcon* developed by Miranda and Fackler (2004). Instead of modeling the risk aversion loss caused by stochastic variations in the resource stock dynamics in the package, we consider the expected loss from a potential regime shift $\lambda(x)(W(x) - \phi(x))$ in our problem. Similar to earlier studies on abrupt environmental changes (Cai et al. 2012) with some percentage loss of GDP, we assume here a certain percentage loss in the optimal value. For example, if the relative loss from a fishery collapse is $\beta = 30\%$, then the post-event value would be $\phi(x) = (1-0.3)\,W(x) = 0.7W(x)$.

We adopt the optimization techniques as Miranda and Fackler (2004) by value function iteration and the collocation method for functional approximation[3]. The first step involves a polynomial approximation of the unknown value function $W(x)$ at a number of n Chebyshev nodes $x \in [x_{min}, x_{max}]$, i.e. $W(x) = \sum_{i=0}^{n-1} c_i x^i$ with an "educated guess" of the coefficients $c_i^0, i = 0, 1, 2, \ldots, n-1$. Such an "initial" value function, say, $W^0(x)$, implies a certain harvest rule and stock dynamics according to (10) and (1). This, in turn, implies a value function $W^1(x)$ in the next iteration according to (11). The next step attempts to fit the value function $W^1(x)$ with a new set of coefficients $c_i^0, i = 0, 1, 2, \ldots, n-1$, in the polynomial approximation. We iterate the process with $j = 0, 1, 2, \ldots,$ until convergence satisfying $W^j(x) - W^{j-1}(x) < \varepsilon$, with ε as a pre-determined tolerance level (the default level is

[3] The Matlab codes are available by request.

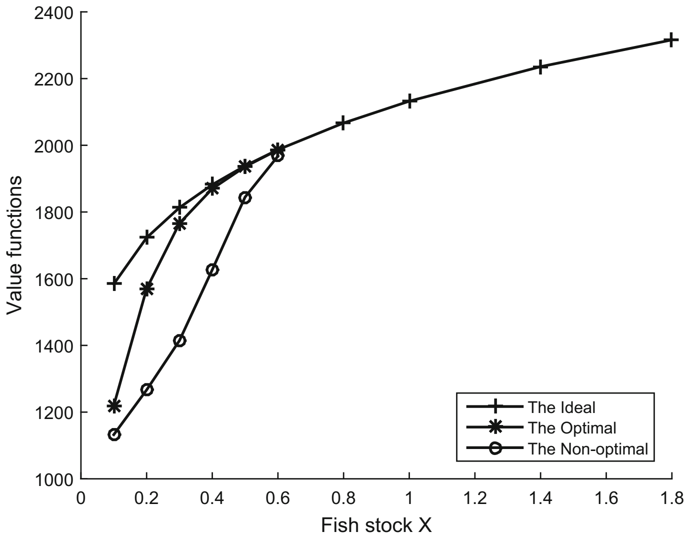

Fig. 1 The ideal, optimal and non-optimal value functions

Table 2 The different value functions and corrective taxes

Resource stock	The ideal value function	Optimal value function	Non-optimal value function	Corrective Tax
X	$\tilde{W}(x)$	$W^*(x)$	$W^0(x)$	$\tau(x)$
0.1	1584	1220	1132	2097.0
0.2	1723	1570	1266	1634.6
0.3	1813	1766	1414	598.5
0.4	1882	1870	1627	174.8
0.5	1938	1936	1845	42.8
0.6	1987	1986	1968	8.4
0.8	2067	2067	2067	0.2
1.0	2132	2132	2132	0.0
1.4	2236	2236	2236	0.0
1.8	2316	2316	2316	0.0

10^{-8}). According to the Weierstrass theorem, any continuous real-valued function $W(x)$ defined on a bounded interval can be approximated to any degree of accuracy by a proper polynomial, and empirical evidence indicates that the Chebyshev nodes are the points for efficient approximation.

Based on the model parameters in Table 1, we study three cases: ideal, optimal and non-optimal as mentioned in Sect. 3. We first study the ideal case in the absence of any risk of a regime shift with the hazard rate $\lambda(x) = 0$ in (11). The resulting ideal value function $\tilde{W}(x)$ under a normal regime is depicted in Fig. 1 (marked by '+') with some sample values reported in the second column in Table 2. By solving the differential equation (11) with the hazard rate defined in (7), i.e. by taking into account the risk of a regime shift, we can determine the optimal value function $W^*(x)$ as shown in Fig. 1 (marked by "*") and in the third column of Table 2.

Compared to the ideal solution, the optimal value is smaller due to the regime shift risk, especially for the lower stock levels. This can be better visualized in Fig. 1, in which the curve marked by '+' depicts the ideal value function, while that marked by '*' the optimal value function. Although the ideal value is higher, it is not attainable without eliminating the flip risks. The optimal value is the best attainable one by trading-off the benefits of harvest and the cost of potential flips. In comparison, the worse case is the non-optimal management where the decision-maker would disregard the real risk of a regime shift, resulting the lowest value function as shown in the fourth column (Table 2) and in the curve marked by 'o' in Fig. 1. Take $x = 0.2$ for example, the non-optimality loss in value becomes $1766 - 1414 = 352$ million US$. In other words, the benefit from harvesting an extra unit of fish cannot cover the cost from the increased flip risk caused by harvesting the extra unit.

By inspecting the three curves in the figure, we can see that they seem to converge to the same curve when the fish stock level increases to a certain level. The reason for this is that the risk of a regime shift becomes virtually zero according to the calibrated probability density function of the stochastic threshold. For example, when the actual stock level is $x = 0.6$, the flip probability is about 0.003. This may imply that a sufficiently high stock provides certain insurance to prevent the regime shift from happening.

From Fig. 1, we can also see that the slope of the optimal value curve is steeper than the non-optimal one. This implies that the assigned shadow price along the optimal value curve is higher than that along the non-optimal one: the difference is mainly due to the insurance or resilience value against the risk of the undesirable regime shift.

To induce the fisheries management to be socially optimal, we may introduce a corrective tax on harvest according to the difference between the two shadow prices. As can be seen from Table 2, the calculated tax rates are extremely high for low stock levels. For $x = 0.2$, for example, the tax rate is about US$ 1635 per tonne, far greater than the demand price $exp\,(6.6262) \cdot 0.2^{-0.1646} \approx US\$984$, which would render any fish harvest unprofitable. The corrective tax rate for $x = 0.3$ is about US$ 599, which together with the harvest cost US$ 404 leads to a total cost of US$ 1003 per tonne. Since the demand price is only $exp\,(6.6262) \cdot 0.3^{-0.1646} \approx US\$920$, harvesting at this stock level is not profitable either. In effect, the higher tax rate would imply a ban on any harvest for the lower stock situations. For the stock from $x = 0.4$ onwards, harvest becomes profitable, and the corrective tax would apply.

It is instructive to decompose the optimal shadow price per tonne of fish stock into two components: the stock service value (for fish production) and the resilience value (for flip risk reduction), as depicted in Figure 2.

It is seen that while the marginal stock service value follows the law of diminishing rate of return, the resilience value of an extra stock (for flip risk reduction) from an economic standpoint has a bell-shaped form. At a relatively higher stock level with a higher ecological resilience, the risk of flip is negligible and thus the effect of an extra stock for flip risk reduction is also negligible. On the other hand, when the resource stock is relatively low with low ecological resilience, the flip risk is very high, and the optimal value as well as the resilience value would be rather low. In this case, the expected economic benefit of reducing the risk would also be small. Mainly in the middle area, where the probability density of the threshold is high, the resilience values are higher.

To examine how the objective functional values and corrective taxes respond to the parameter values of ρ, σ, β and c, we conduct a series of sensitivity analyses as reported in Tables 3 and 4. For the base case, with an arbitrary stock level $x = 0.2$ and $\rho = 0.1$, $\beta = 0.3$, $\sigma = 0.1776$

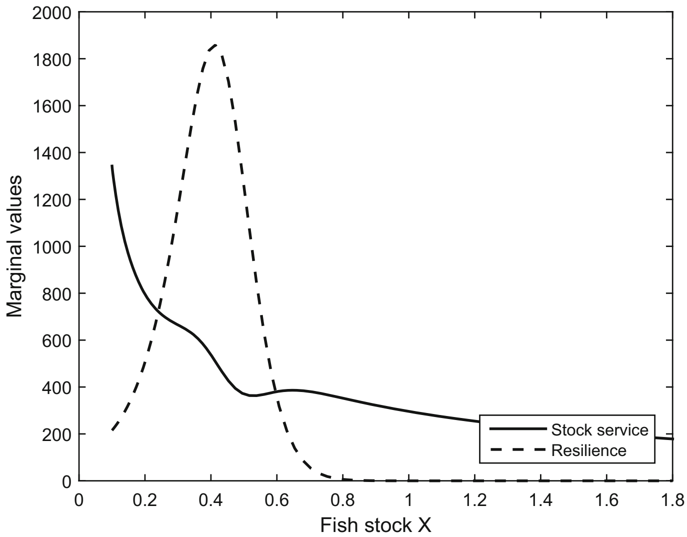

Fig. 2 The resilience and stock service values

Table 3 Sensitivity analysis at low resource stock $x = 0.2$

The cases	Parameter value	Corrective tax $\tau\ (x)$	Ideal value $\tilde{W}\ (x)$	Relative value $\frac{W^*(x)}{\tilde{W}(x)}$	Relative value $\frac{W^0(x)}{\tilde{W}(x)}$
Base case	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.1776, c = 404$	1635	1723	0.91	0.74
$\rho \downarrow$	$\rho = 0.05, \beta = 0.6$ $\sigma = 0.1776, c = 404$	3742	3823	0.91	0.72
$\beta \uparrow$	$\rho = 0.10, \beta = 0.6$ $\sigma = 0.1776, c = 404$	3274	1732	0.82	0.47
$\sigma \uparrow$	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.2131, c = 404$	1745	1732	0.87	0.73
$c \downarrow$	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.2131, c = 202$	2352	2471	0.91	0.74

and $c = 404$, the ideal value in the absence of flip risks is 1723 million US\$. In comparison, the realized value from optimizing the flip risks is about 91 % of the ideal value, whereas the realized value from ignoring the flip risks is only 74 % of the ideal value. The corrective tax is about US\$ 1635 per tonne in this base case. When the rate of time preference ρ is reduced from 10 to 5 %, the ideal value and the corrective tax are more than doubled but the relative values from optimizing and ignoring the flip risks remain almost the same. When the relative loss in present value from a fishery collapse β goes up from 30 to 60 %, we see that the relative optimal and non-optimal values become much lower, as expected. It is interesting to notice that although the ex-post loss from a definite flip would increase by 30 %, the expected value loss in the optimized value is only about 9 % (from 0.91 to 0.82) under proper risk management. In contrast, ignoring the flip risk leads to an expected loss by 25 % (i.e. $0.72 - 0.47 = 0.25$).

Table 4 Sensitivity analysis at the biological threshold $x = 0.4347$

The cases	Parameter value	Corrective tax $\tau(x)$	Ideal value $\tilde{W}(x)$	Relative value $\frac{W^*(x)}{\tilde{W}(x)}$	Relative value $\frac{W^0(x)}{\tilde{W}(x)}$
Base case	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.1776, c = 404$	110	1902	0.99	0.90
$\rho \downarrow$	$\rho = 0.05, \beta = 0.6$ $\sigma = 0.1776, c = 404$	218	4020	0.99	0.85
$\beta \uparrow$	$\rho = 0.10, \beta = 0.6$ $\sigma = 0.1776, c = 404$	211	1902	0.99	0.80
$\sigma \uparrow$	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.2131, c = 404$	260	1902	0.99	0.83
$c \downarrow$	$\rho = 0.10, \beta = 0.3$ $\sigma = 0.2131, c = 202$	146	2735	0.99	0.90

On the fifth row in Table 3, we show how an increased uncertainty from $\sigma = 0.1776$ to $\sigma = 0.2131$ would affect the realized values. It turns out that the results are almost the same as in the base case, indicating that our result "proper risk management improves the optimized objective value" is robust to the probability distributional assumptions on the thresholds. The sixth row in Table 3 shows how the harvest cost per tonne influences the values and tax rate. Lowering the unit harvest cost from $c = 404$ to $c = 202$ would increase the ideal value by 42 % and tax rate by 35 %. When the unit harvest cost is lower, we need to use a higher tax rate to prevent overfishing. A lower unit harvest cost also leads to a much higher optimal value and therefore the relative optimal value with respect to the ideal value is higher. However, ignoring the flip risk under a lower unit harvest cost might not improve the relative non-optimal value.

In Table 4, we repeat the sensitivity analyses of different parameter values of ρ, σ, β and c, but at $x = 0.4347$, the biologically determined threshold level. It is seen that the ideal value in the absence of flip risk varies a lot depending on the model parameters. However, a surprising result is that the maximized functional value from optimal risk management remains approximately the same, i.e. some 99 % of the ideal value. The expected value loss from ignoring the flip risks is in comparison considerably larger. Compared to Table 3, where the fish stock is 0.2, the corrective taxes in Table 4 with a higher fish stock level being 0.4347 are much lower, somewhat between US\$ 100 and 300 per tonne. The reason is that with a higher fish stock, the service value of fish stock is higher. Corrective tax as an instrument for managing fishery becomes less urgent under a higher fish stock and therefore a lower tax rate could be applied.

To see how the optimal trajectory of harvest (with the risk of flip taken into account) differs from the non-optimal trajectory (by ignoring the flip risk), we depict the curves in Fig. 3.

Approximately, from a stock level around 0.75, the trajectories almost coincide with each other, converging to the steady state. Below 0.75, however, the optimal harvest is significantly lower than the non-optimal one. The main reason is that at a lower harvest level, the resulting higher fish stock has a larger insurance or resilience value. It is worth mentioning that, for a constant hazard rate, the steady state under the risk of regime shifts may substantially differ from the steady state without the regime shift risks, as it modifies the effective discount rate.

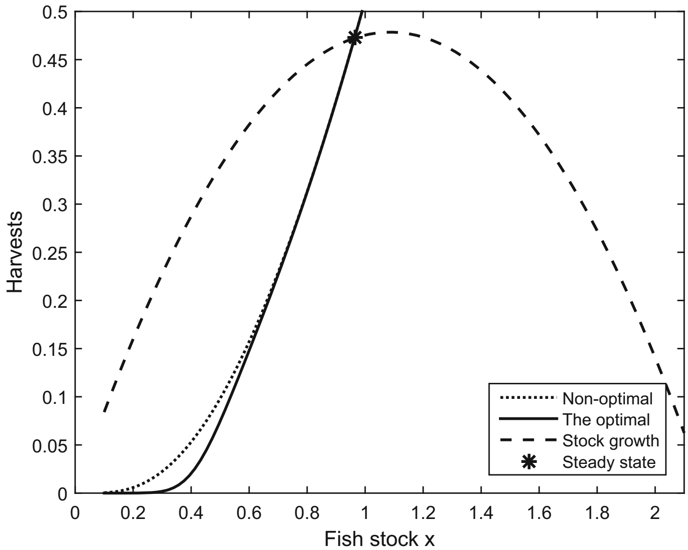

Fig. 3 Optimal versus non-optimal paths and the steady state

In our figure here, however, the steady state remains approximately the same and the reason for this is that, evaluated at the steady state stock level, the hazard rate is virtually zero.

6 Concluding Remarks

Regime shifts in marine resource systems highlight the importance of understanding the resilience and vulnerabilities of the systems for improving management. However, little research has been done on the economic dimension of regime shifts applied to fisheries management.

In this paper we have investigated the role of regime shifts and the interlinkage between ecological and economic resilience in industrial fisheries. Based on a theoretical model where the hazard function is incorporated for resource management under alternative conditions, i.e. with and without taking into account the risk of regime shifts, we derive the corrective tax for fishing activity. Particularly, we applied the model to the case of Argentinean hake fishery to obtain insights for fishery management in the presence of regime shift risks. Using the stock and catch data in 1986–2010, we calibrated the model and derived the logistic growth function of the Argentinean hake fishery. Using the price and consumption data, we derived the demand function.

We distinguished the ideal, optimal and non-optimal value functions in the model for comparison purposes. Using different levels of fish stocks we simulated the three value functions and the corresponding corrective tax rates. The model allows us to illustrate how thresholds and resilience can play a role in marine conservation under different value functions. We obtained robust results, indicating that a higher fish stock leads to higher values but lower tax rates. When the stock level is lower, we need to introduce a higher tax rate to avoid the fishery collapse.

Sensitivity analyses show that a lower discount rate leads to a higher ideal value but the relative optimal value to the ideal value does not change much because the future value is appreciated and the risk of flips is taken into account well. However, the corrective tax rate becomes higher in order to reduce the exploitation of the fish stock. The higher relative loss from the fishery collapse leads to the lower values of ideal, optimal and non-optimal functions as such risk management becomes more effective. A lower unit- harvest cost leads to a higher ideal value but even a higher relative optimal value due to a higher stock service value. A higher fish stock level leads to a lower tax rate because the resilience value of the fish stock is higher and the corrective tax rate as an instrument for managing fishery becomes less important.

It is worth mentioning that we have adopted the standard biological growth model for single species to study the resilience issue and the corrective tax in the presence of a stochastic threshold in the fish stock. Alternative models with more detailed cohort structure and even multi-species fisheries may need to be introduced in the future research. In that case, the single threshold model should also be extended to a model with multiple thresholds for different species and cohorts, and the optimization problem extended to the multivariate stochastic control problem under uncertainty.

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References

Arrow K, Dasgupta P, Goulder L et al (2004) Are we consuming too much? J Econ Pers 18:147–172

Aubone A, Bezzi S, Castrucci R et al (2000) Síntesis del estado de las pesquerías marítimas argentinas y de la Cuenca del Plata. INIDEP N° 1129, Mar del Plata, Argentina

Boltovsky D (1981) Atlas del Zooplancton del Atlântico Sudoccidental y métodos de trabajo con el zooplancton marino, Publicación Especial del Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP), Mar del Plata, Argentina I-XXX, p 938

Cai Y, Judd KL, Lontzek TS (2012) The social cost of abrupt climate change. Working paper prepared for Conference on Climate and the Economy. Stockholm, Sweden, Stockholm University Institute for International Economic Studies

Chapin FS III, Folke C, Kofinas GP (2009a) A framework for understanding change. In: Chapin FS III, Kofinas GP, Folke C (eds) Principles of ecosystem steward- ship: resilience-based management resource management in a changing world. Springer, New York, pp 3–28

Chapin FS III, Kofinas GP, Folke C (eds) (2009) Principles of ecosystem steward- ship: resilience-based management resource management in a changing world. Springer, New York, USA, p 401

Clarke HR, Reed WJ (1994) Consumption/pollution tradeoffs in an environment vulnerable to pollution-related catastrophic collapse. J Econ Dyn Control 18(5):991–1010

Costanza R, de Groot R, Sutton P et al (2014) Changes in the global value of ecosystem services. Global Environ Change 26:152–158

Crépin A-S, Walker B, Polasky S (2011) Global dynamics, multiple shocks and resilience. Planetary stewardship and catastrophic shifts in the Earth system. Beijer Discussion Beijer N° 288, The Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Sweden

Cropper ML (1976) Regulating activities with catastrophic environmental effects. J Enviriron Econ Manag 3:1–15

Dato C, Bambill G, Cañete G et al. (2006) Estimación cuantitativa del descarte en la pesquería de merluza realizado por la flota comercial argentina. INIDEP Documento Científico, pp 31–38

Da Rocha JM, Cerviño S, Villasante S (2012) The Common Fisheries Policy: an enforcement problem. Mar Policy 36(6):1309–1314

de Zeeuw A. (2014). Regime shifts in resource management. Annu Rev Resour Econ 6(1):85–104

Food and Agriculture Organizaiton of the United Nations (FAO) (2014) Argentina. Country profile, 2014. http://www.fao.org/fishery/facp/ARG/es. Cited 14 Dec 2014

Folke C, Jansson Ã, Rockstrom J (2011) Reconnecting to the Biosphere. Ambio 40:719–738

Hughes TP, Bellwood DR, Folke C et al (2005) New paradigms for supporting the resilience of marine ecosystems. Trends Ecol Evol 20(7):380–386

Irusta CG, D'Atri LL (2009) Evaluación del estado del efectivo Norte de 41° S de la merluza (*Merluccius hubbsi*) y estimación de la captura biológicamente aceptable para el año 2010, INIDEP Informe Técnico N° 45, p 39

Irusta CG (2015) Evaluación del estado del efectivo Norte de 41° S de la merluza (*Merluccius hubbsi*) y estimación de la captura biológicamente aceptable para el año 2016, INIDEP Informe Técnico N° 29, p 33

Maler K-G, Li C-Z (2010) Measuring sustainability under regime shift uncertainty: a resilience pricing approach. Environ Dev Econ 15:707–719

Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well- being: synthesis. Island Press, Washington, DC

Myers R, Hutchings J, Barrowman N (1997) Why do fish stocks collapse? The example of Cod in Atlantic Canada. Ecol Appl 7(1):91–106

Pindyck S (1984) Risk, inflation, and the stock market. Am Econ Rev 74(3):335–351

Polasky S, De Zeeuw A, Wagener F (2011) Optimal management with potential regime shifts. J Environ Econ Manag 62(2):229–240

Renzi M, Villarino MF, Santos B (2009) Evaluación del estado de explotacion del efectivo Sur de 41°s de la Merluza (*Merluccius hubbsi*) y estimación de las capturas biológicamente aceptables correspondientes al año 2008 y 2009. INIDEP Informe Técnico Oficial N° 46, p 37

Santos B, Villarino MF (2015) Evaluación del estado de explotacion del efectivo Sur de 41°s de la Merluza (*Merluccius hubbsi*) y estimación de las capturas biológicamente aceptables correspondientes al año 2016. INIDEP Informe Técnico Oficial N° 32, p 40

Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol Evol 18:648–656

Steffen W, Richardson K, Röckstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:6223

Tsur Y, Zemel A (2004) Endangered aquifers: groundwater management under threats of catastrophic events. Water resources research 40(6):1–10

Tsur Y, Zemel A (2006) Welfare measurement under threats of environmental catastrophes. J Environ Econ Manag 52(1):421–429

Villasante S, Sumaila R, Antelo M (2014) Why cooperation is better? The gains of cooperative management of the Argentine shortfin squid fishery in South America. In: Barret S, Maler KG, Maskin E (eds) Environment and development economics: essays in honour of Sir Partha Dasgupta. Oxford University Press, Oxford, pp 270–294

Villasante S, Österblom H (2015) The role of cooperation for improved stewardship of marine social-ecological systems in Latin America. Ecol Soc 20(1):8

Villasante S. Macho G, Isusi de Rivero J, Antelo M, Divovich E, Harper S, Zeller D, Pauly D. (2016) Estimates of total marine fisheries removals from the Northwest of Spain (1950–2010). In: Zeller D, Pauly D. The Atlas of the World Oceans, Inland Press, Washington DC (forthcoming)

Weitzman ML (2003) Income, wealth, and the maximum principle. Harvard University Press, Cambridge, MA