Analysis

Modeling adaptation in multi-state resource systems

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ABSTRACT

A current concern in the economics of natural resources is the role of adaptation in moderating the economic impact of exogenous changes in the resilience of natural resource systems. We develop a bioeconomic model of the exploitation of a renewable resource that can exist in multiple states. We then use this to consider the value of adaptive over non-adaptive policies when there is a change in state, and there are fixed costs of starting or stopping extraction. We take adaptive policies to be those that base extraction on the current state of the system, and the conditioning effect that has on the expected future state of the system. We take non-adaptive policies to be those that base extraction on the long run average state of the system. We find that whether adaptive or non-adaptive policies dominate depends on the fixed costs of starting or stopping extraction. If the fixed costs of closure are very low, non-adaptive policies dominate. However, if the fixed costs of closure are high, adaptive policies are preferred. We use a numerical example based on the Peruvian anchoveta fishery to illustrate the results.

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1. Introduction

Resilience is defined as the capacity of a system to maintain functionality in the face of either stress or shock. It is measured by the size of the disturbance the system can absorb without changing its functional characteristics (Holling, 1973). This translates as the probability that a system in some state will transition to a different state, given some disturbance regime (Perrings, 1998). There are two archetypal management problems posed by regime shifts or state changes. The first is the *mitigation* of the risk of a regime shift, or loss of system resilience (Scheffer et al., 2001; Folke et al., 2004). A familiar example of this approach is the management of fertilizer applications in the catchments of shallow lakes to avoid a shift from an oligotrophic to a eutrophic state (Carpenter and Cottingham, 1997; Scheffer, 1997; Carpenter et al., 1999; Mäler et al., 2003). The second is *adaptation* to exogenous regime shifts (Crépin et al., 2012). The most familiar examples are local adaptations to global climate change (Berkes et al., 2003; Berkes, 2007; Nelson et al., 2007; Adger et al., 2011). We are interested in the second problem.

Building on previous work (Baggio, 2015) we analyze the value of adaptation to change in the probability of state switches in exploited natural resource systems. An example of a natural resource management system that can exist in multiple states is the Peruvian anchoveta fishery, in which the El Niño/La Niña–Southern Oscillation, a quasi-periodic climate pattern, generates alternative states of the system, and alternative population dynamics. We have already noted that the

transition probabilities of the system in some state have been interpreted as a direct measure of its resilience in that state (Perrings, 1998). Here, we are interested in the value of adaptation to changes in the transition probabilities. More particularly, we are interested in the impact on resource rents of management strategies involving a costly decision to open/close the resource to exploitation and we investigate how the magnitude of such cost determines the efficiency of the management strategies.

We show that the value of adaptation in a multi-state system is equivalent to the value of the information adaptation generates. We consider two polar strategies for the management of a natural resource system that can exist in two states. A non-adaptive strategy selects current exploitation rates based on the long-run expected state of the system. An adaptive strategy, by contrast, selects current exploitation rates based on the current state of the system, and the expected future state of the system conditional on the current state. A non-adaptive strategy accordingly requires less information to implement than an adaptive strategy. To determine the relative value of adaptation, we compute the rents associated with each strategy, i.e. the rents associated with exploitation strategies based on partial or full information about the state of the system. If a change in the probability that the system will remain in some state induces a change in extraction policy, this gives us a way to estimate the value of adaptation to changes in system resilience.

Exploiting the classical linear control model developed by (Clark and Munro, 1975), and a regime switching model due to (Nøstbakken, 2006), we investigate the effect of switching dynamics on the optimal extraction of a natural resource. The resource is assumed to fluctuate according to some stochastic process, potentially inducing a switch from one state, and one set of dynamics, to another. We suppose that

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a change in the abundance of a harvested species beyond some threshold induces the closure of the resource, and that the opening/closing of the resource incurs a fixed cost. This implies the existence of two critical values, or thresholds, that trigger the opening or closing of the resource. Our model can be interpreted as an extension of Nøstbakken (2006) to the case of the exploitation of a natural resource with regime-switching dynamics. The formal difference between adaptive and non-adaptive policies lies in the information used to project open and closed states. In the non-adaptive case it is the equations of motion of the resource stock averaged over all states. In the adaptive case it is the equations of motion of the stock in each state, along with the probability that the system will persist in each state.

We analyze the switching process and the population dynamics in each state using a Markov switching model with constant transition probabilities. Since we are concerned with the case where transition probabilities are exogenous to the decision process—we suppose that changes in environmental conditions can alter the probability of transition between states, but that changes in extraction policies cannot. For this case we estimate the value of adaptation to changes in the transition probabilities between states. We show (a) that changes in the probability that the system will persist in one or other state has a significant impact on resource rents under both strategies, (b) that the value of adaptation is highly sensitive to the fixed cost of closures, and (c) that policies addressing the fixed costs of closures accordingly offer potential benefits in terms of the gains to adaptation.

The paper is organized in six sections. Section 2 describes a continuous time model of the optimal management of a natural resource with switching behavior under adaptive and non-adaptive strategies. A discrete-time numerical example, based on the Peruvian anchoveta fishery, illustrates the approach in Section 3. Section 4 then reports the implications for the value of adaptation. Section 5 offers a discussion of the implications of this for policy, and a final section offers our concluding remarks.

2. A Model With Switching Behavior

We model the dynamics of a natural resource, denoted $x(t)$, in which the critical parameters vary between states of nature, denoted s. The stock is assumed to grow according to a logistic function

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

where $y(t)$ denotes instantaneous harvest, and the parameters r_s (the intrinsic growth rate of the resource) and K_s (the carrying capacity of the environment) take different values in different states of nature. The volatility of the stock dynamics, $\sigma_s x(t)$, is likewise different in different states of nature, and dW is a white noise Wiener process characterizing the environmental shocks to the system.

We assume that the state of nature, s, is observable and that the probabilities of transitioning between states follows a Poisson law such that $\{s\}$ is a Markov chain alternating between two states, i.e., $s = 1, 2$ (Perrings, 1998; Guo et al., 2005). If $\lambda_{s,s} dt$ denotes the probability of remaining in state s in the interval time dt, a complete representation of the transition between states is given by the probability matrix

$$\Lambda = \begin{bmatrix} \lambda_{1,1} dt & 1-\lambda_{1,1} dt \\ 1-\lambda_{2,2} dt & \lambda_{2,2} dt \end{bmatrix}. \tag{2}$$

The time spent in each state is a continuous-time stochastic process with the Markov property that future evolution of the system depends only on the current state. The transition probability matrix is assumed to be irreducible, implying that there are no absorbing states. That is, $0 < \lambda_{s,s} dt < 1$, and $\lambda_{s,s'} = 1 - \lambda_{s,s}$ implying that there is some probability of a change from one state to another in the interval of time dt. The

probabilities are assumed to be exogenous and thus cannot be influenced by the extraction policy. However, we do allow one state to be encountered more frequently than the other if $\lambda_{s,s'} = \lambda_{s',s}$ implies that the system is more persistent in state s' than it is in state s.

We suppose that the resource is owned/operated by a single entity, which selects an extraction policy to maximize the expected present value of the future stream of rents subject to the dynamics of the resource (1) and (2) in each of two possible states of nature. While this is only one of many institutional arrangements governing the extraction of natural resources, we wish to abstract from the complexities posed by institutional conditions involving common or communal property rights, open access, regulated or partially regulated access and so on. Following Nøstbakken (2006) we assume that starting or stopping harvest incurs a fixed cost a This implies that the decision problem is of the form:

$$V(x(t),s) = \max_{y(t)} E\left\{ \int_0^\infty e^{-\delta t}([p-c(x(t))]y(t)-a(t))dt \right\} \tag{3}$$

in which $p - c(x(t))$ is the unit price of the harvested resource net of the cost of extraction, a function of the size of the stock, and $a(t)$ is the fixed cost of decisions to close or open the resource at time t. Since the associated Hamiltonian function is linear in the control we expect the optimal harvest trajectory to follow a most rapid approach path. If the stock size is below the optimal level, harvest will be zero, $y(t) = 0$. If it is above the optimal level, harvest will be at full capacity, $y(t) = y_{max}$. In the absence of fixed costs this strategy would converge on the singular solution as quickly as possible. If there fixed costs, however, if it is optimal to change the harvest rate in any way at any point along the trajectory, it will be optimal to switch between zero and y_{max} (Nøstbakken, 2006).[1] The optimal harvest will be pulsed, incurring fixed costs whenever harvest either begins or ends: $a(t) = 0$ if $dy/dt = 0$, $a(t) = a$ if $dy/dt \neq 0$.

We expect changes in harvest rates to be triggered by changes in stock size. That is,

$$y(t) = \begin{cases} 0 & \text{only if } x(t) \leq x^*_{s,close} \\ y\,max & \text{only if } x(t) \leq x^*_{s,open} \end{cases} \tag{4}$$

where $x_{s,close}{}^*, x_{s,open}{}^*$ is the minimum/maximum stock size in state s that induces the opening/closure of the resource. Note, however, that the speed with which the resource manager actually adjusts to a change in state depends on the fixed cost of opening or closing the resource. Extraction will be delayed even if warranted by a change of state if the net benefits of extraction are less than the fixed costs of opening the resource. Similarly, extraction may persist even if a change of state means that the current stock level is lower than the optimal stock level, if the fixed costs of closing the resource are too high. This is a similar problem to the entry–exit decisions of a firm under uncertainty (Dixit and Pindyck, 1994).

2.1. Non-adaptive and Adaptive Management

In what follows we consider two management strategies: adaptive and non-adaptive. The difference between the two strategies lies in the information that is used to make decisions, and the way that information is updated. Non-adaptive management makes use of less information about the dynamics of the resource, and does not update information. Adaptive management makes use of more information on the resource dynamics, and does update that information.

We take the *non-adaptive* problem to be the maximization of the discounted stream of future net benefits subject to the long-run average dynamics of the resource, that is, the biological parameters r, K, and σ

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[1] The presence of fixed costs leads to nonconvexity of the cost function, which is what favors pulsed extraction over constant extraction (Clark, 2010).

are single valued. We assume that a cost is incurred every time that the resource is open or closed equal to a. We also assume that the cost of extraction takes the form $c(x(t)) = c/x(t)$, implying that extraction costs are decreasing in the size of the stock The Hamilton–Jacobi–Bellman (HJB) equation in the non-adaptive case is

$$\delta V(x(t)) = \max_{y(t)} \left\{ \begin{array}{l} (p-c/x(t))y(t)-a(t)+ \\ [rx(t)(1-x(t)/k)-y(t)]V_x + \frac{1}{2}\sigma^2 x(t) V_{xx} \end{array} \right\} \qquad (5)$$

where the value function, V, depends on the size of the stock and whether or not the resource is open or closed. Because of the presence of fixed costs, this optimization problem yields an extraction strategy characterized by two thresholds that trigger 1) the opening and 2) closing of the resource. At each moment in time, the resource manager compares the stock level to the thresholds and determines whether it is optimal to open or close the resource. The two thresholds are independent of the current state of the system. The resource is thus managed as if there were no switching dynamics. This policy corresponds to the management of a natural resource with stochastic dynamics but a single state as described (e.g.) in Brekke and Øksendal (1994) and Nøstbakken (2006).[2]

In the *adaptive* case, by contrast, the resource manager takes account of potential changes of state, and determines the optimal closure policy accordingly (maximizing (3) subject to the stock dynamics (1) and (2)). That is, after observing the current state of the resource, the resource manager chooses whether to maintain or to change the status of the resource. The combination of the two states of nature ($s = 1, 2$) and the two management options (open/closed) gives four potential cases: ({1, *closed*}, {1, *open*}, {2, *closed*}, {2, *open*}). The HJB equation has the form

$$\delta V(x(t),s) = \max_{y(t)} \left\{ \begin{array}{l} (p-c/x(t))y(t)-a(t)+ \\ [r_s x(t)(1-x(t)/K_s)-y(t)]V_x + \frac{1}{2}\sigma_s^2 x(t) V_{xx}+ \\ \lambda_{s,s'}[V(x(t),s')-V(x(t),s)] \end{array} \right\}. \qquad (6)$$

The solution of the HJB equation accordingly depends on the stock values that trigger the opening or closing of the resource in each of the two states of nature. It generates a pair of threshold values of x, one that triggers the closing and the other that triggers the opening of the resource, for each state of nature. These define the range of stock levels at which it is optimal to exploit the resource.

Notice that the non-adaptive (partial information) HJB equation is nested within the adaptive (full information) HJB equation. The term $(p - c/x(t))y(t) - a(t)$ is the net benefit of current extraction, where p is the price of the resource, $c/x(t)$ is the marginal cost of extraction, and $a(t)$ is the fixed cost of opening or closing the resource.[3] This term is common to both problems. The remainder of the right-hand side is composed of the capital gain due to the growth of the stock, and the expected value of state shifts, i.e., the probability weighted change in resource value due to a change in state. This last term is unique to the adaptive problem, and is equal to the value of the resource after a switch minus the value of the resource before the switch, $\lambda_{s,s'}[V(x(t),s')-V(x(t),s)]$.

If stock dynamics are characterized by constant biological parameters, the last term drops out of Eq. (6) and it becomes the same as Eq. (5). Hence, for a single-state Eqs. (5) and (6) yield the same solution. If there are two states of nature the solution to (6) gives the optimal policy, which consists of two thresholds for each state of the resource dynamics. Specifically, $x_{(s,close)}$ denotes the stock level that triggers the
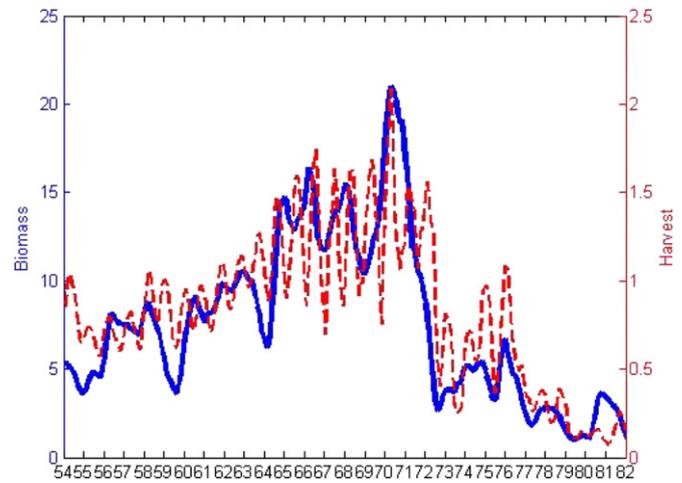

Fig. 1. Biomass (solid line) and harvest (dashed line) for the Peruvian anchoveta fishery, million of metric tons, over the observed time period.

opening of the resource, once it is crossed from above, and $x_{(s,open)}$ denotes the stock level triggering the opening, once it is crossed from below. In state s, for $x(t) \leq x_{(s,close)}$ it is optimal to close the resource, while for $x(t) \geq x_{(s,open)}$ it is optimal to open it. The extraction policy then determines the level of extraction in each state as a function of the costs and revenues of harvest in that state, the growth parameters of the exploited resource in each state of nature, the social discount rate, extraction capacity, and the probability that the system will transition from one state to another.

The resilience of the system in a particular state is (exogenously) given by the probability that it will transition to the alternative state. The marginal value of the resilience of the system in some state accordingly depends on the relative value of the resource in that state:

$$\frac{dV(x,s)}{d\lambda_{s,s}} = \int_{\lambda_{s,s}^0}^{\lambda_{s,s}^1} V(x,s;\lambda_{s,s}) d\omega. \qquad (7)$$

A decline in the resilience of the system in a low productivity state offers welfare gains because it increases the likelihood of transition to a high productivity state, and vice versa. The value of the resource in any state is, in turn, a function of the length of time it can profitably be exploited in that state. This depends on the productivity of the resource, and on the net benefits of extraction relative to the fixed costs of opening or closing. An adaptive strategy that responds rapidly to changes in the state of nature will dominate a non-adaptive strategy if and only if the gains it yields in terms of extra extraction exceed the costs incurred in more frequent resource openings/closures.

3. Adaptive Management of a Multi-state Resource Systems: A Numerical Example

To show the factors that affect the returns to adaptive versus non-adaptive responses to changes in ecosystem resilience, we calibrated a discrete time version of the model described in Eqs. (1)–(7) on annual data from an archetypal multi-state resource system, the Peruvian anchoveta fishery. The Peruvian anchoveta—a short-lived species located along the coast of northern and central Peru (4°S and 14°S)—experiences large fluctuations in biomass due to the alternating of cold/warm phases corresponding to La Niña/El Niño climatic event (Lluch-Belda et al., 1989; Chavez et al., 2003). In each state of the system there are different stock-recruitment relationships, different growth rates, and different density dependence effects (see, for example, Cahuin et al., 2009). Since the 1960s catch has been limited by closures and quota, the total allowable catch being sharply reduced during El

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[2] The model presented in Nøstbakken (2006) also includes stochastic price. The price is non-stochastic in our model.

[3] We assume that the production of the resource is not large enough to influence market price. Hence, demand is assumed to be perfectly elastic at the market price.

Niño events (Clark, 1977).[4] This is an example of switching dynamics. While we do not attempt to replicate the institutional conditions of the fishery, we do seek to capture these features of the biophysical system.

To understand the effects of the persistence of the system in each state, we estimated the stock dynamics using data on monthly biomass obtained from virtual population analysis and catches for the period 1953–1982 (for details see Pauly and Palomares, 1989).[5] A 5-month running average was used to smooth the data to reduce the effects of seasonality in biomass and catch. Fig. 1 presents the smoothed data for biomass and harvest in million of metric tons. Over the observed period, the average and standard deviation are 7.623 and 4.688 for the biomass, and 0.823 and 0.424 million of tons for the harvest. The regression equation for the switching population dynamic was specified as

$$\frac{x_t - x_{t-1} + y_{t-1}}{x_{t-1}} = r_s + \frac{r_s}{K_s} x_{t-1} + \varepsilon_t \tag{8}$$

where the dependent variable is the biomass rate of change, and the independent variables are the intrinsic and stock-adjusted growth rates of the resource in the current state. The error term ε is assumed normally distributed with zero mean and variance σ_s^2. The parameters of the regression model depend on the realization of s, and hence on the transition probabilities between states. The probability that the system in a particular state s will remain in that state takes a logistic functional form

$$\lambda_{s,s} = \frac{\exp(\alpha_s)}{1 + \exp(\alpha_s)} \tag{9}$$

where α_s is a constant expressing the baseline resilience in the state s, with $s = 1, 2$. The parameters α_1 and α_2 are estimated jointly with those of Eq. (8) for a total of eight parameters: $r_1, r_2, \frac{r_1}{K_1}, \frac{r_2}{K_2}, \sigma_1^2, \sigma_2^2, \alpha_1, \alpha_2$. Eq. (9) provides a quantitative measure of the resilience of the system in each state. A logistic specification for the transitional probabilities is often used in the empirical literature for Markov switching models (Diebold et al., 1994; Kim and Nelson, 1999). However, the application of Markov switching models with time-varying probabilities in the literature on the management of renewable resources is very recent (e.g., Baggio, 2015).

The models (8)–(9) is estimated using a Markov switching regression with constant transition probabilities, where a likelihood function is maximized using the Expectation-Maximization EM algorithm where the dates of the shifts are not known a priori (Hamilton, 1990).[6] Table 1 shows the estimates. All coefficients were found to be significant at the 1% level and to have the expected sign. The estimates reflect the differences in system dynamics between the alternative states. The intrinsic growth rate was found to be three times larger in state 2 than in state 1. That is, the system is inherently more productive in state 2 than in state 1. However, state 2 also showed much stronger density dependent effects than state 1, and biomass was more variable. In addition, while anchoveta were found to grow more slowly in state 1

Table 1
Markov switching regression model.

Variable	Coeff.
r_1	0.0984
r_1/K_1	−0.0009
σ_1^2	0.0019
α_1	3.3790
r_2	0.2848
r_2/K_2	−0.0078
σ_2^2	0.0022
α_2	1.7898
Log likelihood	538.0810
N. obs.	336
Transition probabilities	
$\lambda_{1,1}$	0.9670
$\lambda_{1,2}$	0.0330
$\lambda_{2,1}$	0.1431
$\lambda_{2,2}$	0.8569

Note: All coefficients are significant at 1% level. The lambdas are calculated from the estimated α_s using the expression $\lambda_{s,s} = \exp(\alpha_s)/(1 - \exp(\alpha_s))$, with $s = 1, 2$.

the carrying capacity of the system was found to be higher. In other words, the system could achieve greater biomass in state 1 than in state 2. Given the differences in the growth rate and the density dependent effects, state 1 is defined as the low productivity state and state 2 as the high productivity state.[7] We estimated the probability that the system in state 1 would remain in that state to be 0.9670, and the probability that the system in state 2 would remain in that state to be 0.8569. So while both states were found to able to withstand large shocks before switching to the alternative state, the system was found to be more persistent in the first state than the second. That is, it takes a larger shock to switch it from state 1 to state 2 than from state 2 to state 1.

To find the optimal harvest policy, we set fleet capacity equal to the highest catch rate observed in the sample period 1953–1982, $y_{max} = \max(y_t/K_2) = 0.0851$, where K_2 denotes the carrying capacity of the high productivity state 2. The normalized parameters for the problem are the fish price, taken to be the numeraire, $p = 1$,[8] the relative unit cost of harvest, $c = 0.33$, the relative opening and closing fixed costs of harvest, $a_{open} = a_{close} = 0.1$, and the discount rate, $\delta = 0.075$. Since data on the cost structure of the Peruvian fishery were not available and our assumptions for the unit cost of harvest and discount rate are based on data from the Chilean pelagic fishery included in Aguero and Gonzales (1996).[9] As a baseline we assumed that the fixed costs of opening or closing the fishery were equal to 30% of the cost of harvest, but we also tested the sensitivity of the results to this assumption.

Taking the coefficients for the estimated dynamics and these parameters, the numerical solution of Eq. (6) yielded optimal closing/opening thresholds of 0.5779/1.1598 of K_2 for state 1, the low productivity state, and 0.4377/0.8864 of K_2 for state 2, the high productivity state.[10] This means that for stock levels below 0.4377 no fishing occurs regardless the state of the system. As the stock rebuilds, the fishery opens when the stock level reaches a threshold of 0.8864 K_2 (if in the high state), or 1.1598 K_2 (if in the low state). As the stock declines, however, the

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[4] After the El Nino event of 1972, after catching 4.5 million tons in the first months of the year the fishery was closed until March of 1973 and opened sporadically in the following years (Clark, 1977). This indicates that it was common management practice to shut down the fishery when surveys indicated that stock was too low.

[5] The catches are given by the total withdrawals of anchoveta obtained by multiplying nominal catch by a factor of 1.2, adding consumption by guano birds, bonitos and seals to account for unreported catches and natural predation. For details see Pauly and Palomares (1989), downloadable from http://www.seaaroundus.org/researcher/dpauly/PDF/1989/Books&Chapters/NewEstimatesMonthlyBiomassRecruitmentRelatedStatisticsAnchov.pdf (last accessed 01/23/2015).

[6] The shifts are treated as unobserved structural events that are inherent in the data-generating process (Hamilton, 1989). The EM algorithm is robust with respect to poorly chosen starting values and quickly approaches reasonable likelihood maximum (Hamilton, 1990).

[7] These two states can be considered to be the result of the alternating of cold/warm phases corresponding to the La Niña/El Niño climatic event. That is, a favorable, cold, phase represented by state 1 and an unfavorable, warm, phase represented by state 2. This argument is analyzed in Baggio (2015).

[8] Products derived from anchovy are traded as commodities on the international market. Peru is generally considered as a price taker (Pauly and Tsukayama, 1987), hence we assume that demand is perfectly elastic.

[9] In their book, the analysis is done for a discount rate of 5 and 10%. Thus, we assume an average of the two.

[10] Note that both values are relative to the carrying capacity of state 2. The numerical solution is obtained as outlined in Baggio (2015) and using the OSSOLVE solver described in (Fackler, 2004).

fishery remains open until the stock falls below $0.5779\,K_2$, if the system is in a low productivity state, or below 0.4377 if system is in a high productivity state. That is, it is optimal to delay the opening and anticipate the closing of harvesting more in the high productivity state, state 2, than in the low productivity state, state 1.

4. The Effects of Adaptation on Resource Rents

The main effect of a change in the transition probabilities is to change the optimal harvest policy over states of nature. A change in state transition probabilities alters expected stock biomass. This affects the optimal harvest and hence the rents secured by the fishing industry. Comparison between the returns to the optimal strategy over states of nature under adaptive and non-adaptive strategies offers a measure of the value of adaptation to an exogenous change in the persistence of the system in any one state.

The usual approach to the estimation of the value of the resilience of ecosystems has been to treat it as a form of insurance (Baumgärtner, 2007; Barbier et al., 2009). Because the probability that ecosystem services will be compromised by a change in state is lower the greater the resilience of the system, resilience is taken to insure risk-averse resource users against potential welfare losses (Baumgärtner and Strunz, 2009). The probability of remaining in each state can be interpreted as the resilience, or persistence, of the state itself (Perrings, 1998). When the probability of remaining in one state is very high, e.g., close to one, it implies that a change of state is rather unlikely; hence the resilience of the state is high. In the Peruvian anchoveta case, each state yields a flow of benefits with some probability. Here we compare the welfare effect of a change in the persistence of some state where closure rules respond to the change (the adaptive policy) and where they do not (the non-adaptive policy). This provides a measure of the value of the adaptive policy.

To estimate this we simulated the effects of changes in the transition probabilities on resource biomass and rents under adaptive and non-adaptive strategies. We proceeded via the steps described in Fig. 2. First, we selected a vector of points evenly spaced by 0.05 unit points in the range 0–1 for the probabilities of remaining in either state: $\lambda_{1,1}$ and $\lambda_{2,2}$. This gave a total of 440 state combinations, $n = 1, \dots, 440$. To track the effects of a non-adaptive policy, we first estimated stock dynamics for the non-switching case. The OLS estimates for the intrinsic growth rate and density dependence effects are, $r = 0.1411$ and $r/K = -0.0033$, respectively, and they are both significant at 1%; with $\sigma^2 = 0.0046$. For these parameters, the solution of Eq. (5), yields a closing threshold of 0.4568 and an opening threshold of 0.9195. Notice again that the Bellman equation in this case is similar to Eq. (6), but omits the last term on the right hand side.

In the adaptive case, whether the industry is open or closed depends on the value of the stock relative to the optimal thresholds specific to the state of nature. These were obtained from the solution of the HJB Eq. (6). For each possible combination we obtained the optimal thresholds for when the fishery, should be open or closed. Fishing activity was stopped when the stock fell below the closing threshold, and opened when it rose above the opening threshold, and maintained its status otherwise. Because the thresholds are state-specific, knowing the state of nature and whether the fishery is open or closed gives the necessary information to calculate the stock over the whole period. At each point in time, the state of nature was chosen randomly drawing from a Bernoulli distribution with mean equal to the steady-state probability of state 2. The steady-state probabilities for the states were then calculated as $\rho_1 = (1 - \lambda_{2,2})/(2 - \lambda_{1,1} - \lambda_{2,2})$ for state 1 and $\rho_2 = (1 - \lambda_{1,1})/(2 - \lambda_{1,1} - \lambda_{2,2})$ for state 2. This gave a vector of 1200 draws of the state of nature, which defined the active state in period t.

The sequence of states affects the growth of biomass. For instance, an interval of T periods involving alternating states gives a different biomass than an interval of T periods in which the state remains constant. To allow for a sufficient variation in the sequence of states the draws
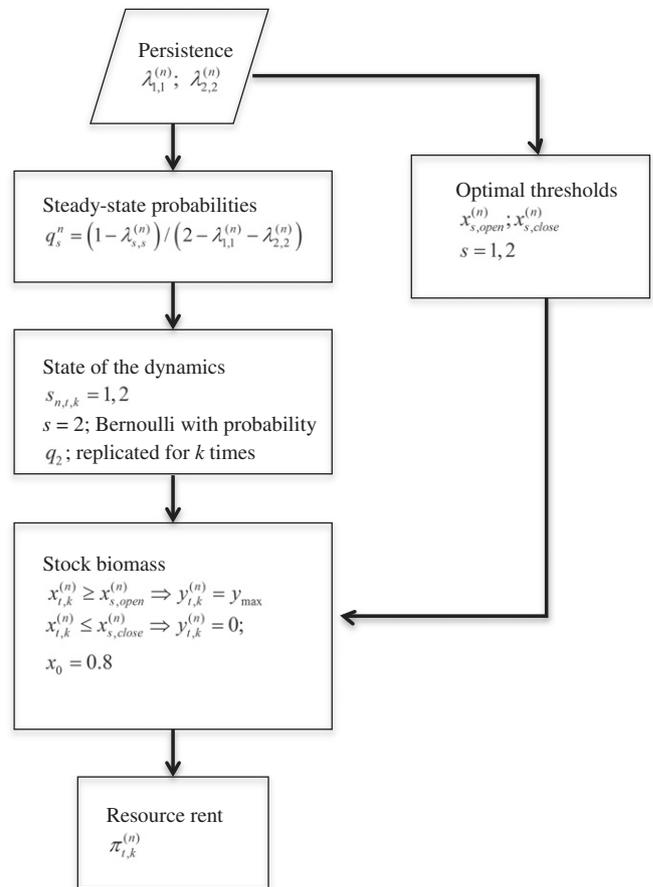

Fig. 2. Flowchart of the simulation analysis.

were replicated 1000 times, $k = 1, \dots, 1000$. This gives 1000 sequences of the population dynamics. Starting from an initial value for the stock of 0.8, and given the state of nature and the opening and closing thresholds, we obtain the stock for the next period and for (monthly) time steps for twelve hundred time steps, $t = 1, \dots, 1200$.

Estimates of biomass and profit were obtained for all replications in the following manner. The simulation yielded a vector of biomass x_{ntk} and instantaneous profit π_{ntk}. Biomass was then averaged over the replications and the whole time period $x_n = \sum_t^T \left(\sum_k^K x_{ntk}/k \right)/T$. The proportion of time that the industry was open was given by $\rho_n =$

Table 2
Estimates of the effects of the probability of being in states 1 and 2 on mean biomass, NPV of fishery rent, and the share of time the fishery is open using an adaptive strategy.

	Biomass	Rent	Open industry
const	0.8667(***)	4.7293(***)	0.6504(***)
$\lambda_{1,1}$	−0.7115(***)	1.4571(***)	−0.2415(***)
$\lambda_{2,2}$	−0.0403	−0.3763(***)	−0.1474(***)
$\lambda_{1,1}^2$	1.2191(***)	−3.0204(***)	0.1992(***)
$\lambda_{2,2}^2$	−0.1984(**)	1.3472(***)	0.2684(***)
$\overline{R}^2$	0.8293	0.8835	0.5586
N. obs.	440	440	440
Mean elasticities			
$\lambda_{1,1}$	0.4857	−0.3342	0.0254
$\lambda_{2,2}$	−0.2098	0.1485	0.1663

Note: Double asterisks (**), and triple asterisks (***) denote significance at 10%, 5%, and 1% level.

$\sum_{k}^{K} \rho_{nk}/k$. The fishery rent was obtained by calculating the present value of the instantaneous profit π_t over the whole period as $\pi_{nk} = \sum_{t=0}^{T} \pi_{ntk}(1/1+\delta)^t$. After that the average rent was calculated as $\pi_n = \sum_{k}^{K} \pi_{nk}/k$. This is the expected present value of the future rents that can be extracted from the resource for each combination of probabilities.

To determine the strength of the adaptive response to changes in state transition probabilities we then estimated models of the effect of resilience, i.e., the probability of remaining in the current state, on the performance of the fishery, measured by its profitability and the proportion of time it is open, as well as on the status of the fish population, measured by stock biomass. The structure of the estimated model was:

$$Z_n = \gamma_0 + \gamma_1 \lambda_{n,(1,1)} + \gamma_2 \lambda_{n,(2,2)} + \gamma_3 \lambda_{n,(1,1)}^2 + \gamma_4 \lambda_{n,(2,2)}^2 + \eta_n \qquad (10)$$

where $Z = (x, \pi, \rho)$ and η_n is a white noise error term. This specification was estimated using the simulated data for mean biomass, the NPV of fishing rent, the proportion of time the fishery was open, and the probabilities of being in state 1 or 2. Estimates for the adaptive case are presented in Table 2. We found mean biomass to be an increasing and convex function of the persistence of state 1, and a decreasing and concave function of the persistence of state 2. This suggests that the average stock biomass increases with the persistence of state 1 and decreases with the persistence of state 2 at an increasing rate. We further found that the net present value of fishery rents was decreasing and concave in the persistence of state 1, while it was increasing and convex in the persistence of state 2. Welfare was therefore decreasing in the persistence of state 1 at an increasing rate, and increasing in the persistence of state 2 at an increasing rate. The proportion of time the fishery was open is increasing and convex in the persistence of both states. That is, it is increasing in the persistence of each state at an increasing rate.

As a measure of the sensitivity of the system indicators to changes in state transition probabilities, we estimated the elasticity of fish biomass with respect to the probability of each state, resource rents and the proportion of time the fishery was open. We found that increasing the persistence of state 1 by 1% increased mean biomass by 0.49% while it decreased rent by 0.33%. The proportion of time the fishery is open was also increasing in state 1 by 0.025%, although the mode of the empirical distribution of the elasticity in negative.[11] The effects of changes in the resilience of state 2 were the opposite. A 1% increase induced a decrease of 0.21% in mean biomass, and a 0.15% and a 0.17% increase in rent and the time the industry was open to fishing, respectively. Increasing the persistence of the low productivity state increased stock conservation while decreasing resource rent and had a negligible effect on the proportion of time the fishery was open. Increasing the persistence of the high productivity state had the opposite effect. The magnitude of the effects on mean biomass was larger than the effects on rent or the period during which the fishery is closed. Indeed the welfare effects of an increase in resilience were found to be very small. The impact on the period during which the fishery was open was similarly small.

Closing costs determine the length of time the resource is open, and so its profitability, under both strategies. Fig. 3 presents the optimal thresholds as functions of the closing costs for both adaptive and non-adaptive strategies. There are two sets of lines, upper opening and lower closing optimal thresholds, under the non-adaptive management (dash-dot green lines), and two sets for state 1 under adaptive management (solid blues lines), and two for state 2 (red dashed lines), adaptive
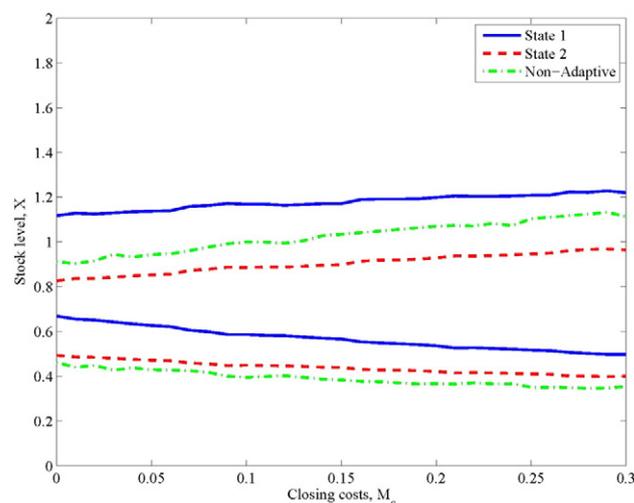
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[11] Empirical distributions for the elasticities may be obtained from the authors on request.

Fig. 3. Optimal opening and closing thresholds for adaptive (state 1 — solid blue lines, and state 2 — dashed red lines) and non-adaptive fishery management policies (dashed-dot green lines) as function of closing costs. The stock level, X, is relative to the carrying capacity of state 2. Notice that the upper lines represent the opening thresholds while the lower lines represent the closing thresholds.

management. When closing costs increase, the fishery operator may delay closing the fishery if profitability is not large enough to sustain these costs. This means that increasing the fixed costs of closing the fishery pushes down the closing threshold, delaying the moment at which fishing stops. In this situation, it is optimal for the fishery operator not to stop fishing until the situation has worsened to the point that it is worth incurring the closing costs. Increasing fixed costs also has indirect effects. Increasing closing costs will, for example, push up the opening threshold because higher closing costs reduce the value of the open fishery. When the system is in state 1, and the fishery operator ignores the existence of switching stock dynamics (the non-adaptive case), it is optimal to delay both the closing and the opening a little bit more than in the adaptive case. However, opening occurs at lower stock levels. When the system is in state 2, the fishery would be open for less time in the non-adaptive case than in the adaptive.

To find the effects of changing closing costs, we simulated the effect on biomass, rents, and the share of time the fishery is open under the non-adaptive case and then compared the results to those simulated for the adaptive case. Fig. 4 shows the comparisons, each panel describing the ratios of the performance of the fishery for the two cases. For instance, panel (a) shows the ratio of the share of time the industry is open under the adaptive and the non-adaptive case, resource rents, $\rho_{\bar{n}}^{\text{adaptive}}/\rho_n^{\text{non - adaptive}}$. It indicates that for closing costs below about 0.1 the non-adaptive policy yields longer fishing time than the more flexible harvest policy. When closing costs are higher the effect is reversed in favor of the adaptive policy. For closing costs below 0.25, the adaptive policy yields gains in mean stock biomass, panel (b). Furthermore, it shows that in the range 0.1–0.25 even if fishing occurs for longer time, a more flexible management strategy will yield higher stock biomass.

The relative performance on NPV of rents also depends on the size of the closing costs. Specifically, the non-adaptive policy yields higher rents than the adaptive policy for low closing costs, i.e., below 0.1, panel (c). The impact of closing costs on the time the fishery is open is monotonically decreasing in state 2 but is non-monotonic in state 1 (Fig. 5, upper panel). Interestingly, in state 1, the share of time that the fishery is open rapidly increases as closing costs rise, reaching a maximum between 0.15 and 0.2, and then starts declining. Rents are, similarly, first increasing and then decreasing. The turning point occurs at closing costs of around 0.15 (Fig. 5, lower panel). Overall, these results suggest that when closing costs are low it is welfare improving to ignore changes in transition probabilities, but as closing costs rise adopting a

state-dependent fishing policy is the better option. The higher the cost of fishery closures, the greater the incentive to improve the precision of stock forecasts. Indeed, the ability to predict future stock biomass can lead to economic benefits when this is incorporated in management strategies. Fig. 6 compares the NPV of rents for adaptive and non-adaptive policy as functions of the closing costs. It appears evident that contrary to those with the adaptive policy, the rents obtained with non-adaptive management are monotonically decreasing in closing cost.

5. Implications for Policy and Conclusions

In this paper we consider the optimal exploitation of a natural resource that can exist in multiple states. Specifically, we consider the effects of changes in the resilience of the system in different states of nature for management under adaptive and non-adaptive extraction strategies. The approach was illustrated using a numerical example based on a classic multi-state resource: the Peruvian anchoveta fishery. The anchoveta fishery is not, of course, unique. Indeed the same drivers of the state of the anchoveta fishery drive state shifts in many other natural resource systems. We model an extraction policy for such a natural resource in order to explore the payoff to adaptation when there is variation in the persistence of particular states, and when the policy itself does not affect the persistence of the state. That is, we consider the case where the level of harvest affects the size of the stock in some state of the system, but it does not affect the likelihood that the state of the system will change.

We find that whether or not adaptation is an efficient strategy depends critically on the cost of resource openings/closure. If the cost of openings/closure is low a non-adaptive policy dominates an adaptive policy. If the cost of openings/closure is high the reverse is true. In our example, an increase in the persistence of the low productive state paradoxically increases stock biomass because it leads to higher conservation. However, since the industry remains open for less time under any policy, the overall effect on welfare is negative. The opposite occurs when the more productive state becomes more persistent.

We find that changes in the persistence of the system in some state affect rents. Specifically, a decrease in the persistence of a less productive state produces welfare gains because it increases the likelihood of transition to the more productive state. The opposite occurs for an increase in the persistence of a less productive state or a decrease in the persistence of a more productive state. The value of extraction in any state is driven by the length of time that the resource is open. This, in turn, is driven by the fixed costs of opening or closing the resource. A flexible extraction policy such as the state-dependent management described in this paper will involve more frequent closures (and openings) because it reacts to changes in the state of the stock dynamics. It follows that the value of adaptation as a fishery management policy depends both on the net benefits of extraction and on the fixed costs of closure. Where changes in transition probabilities have significant costs in terms of forgone rent, a policy that alters the fixed costs of closures can offer significant benefits.

The value of an adaptive versus a non-adaptive strategy is measured by the impact on rents of the information guiding each strategy. We find
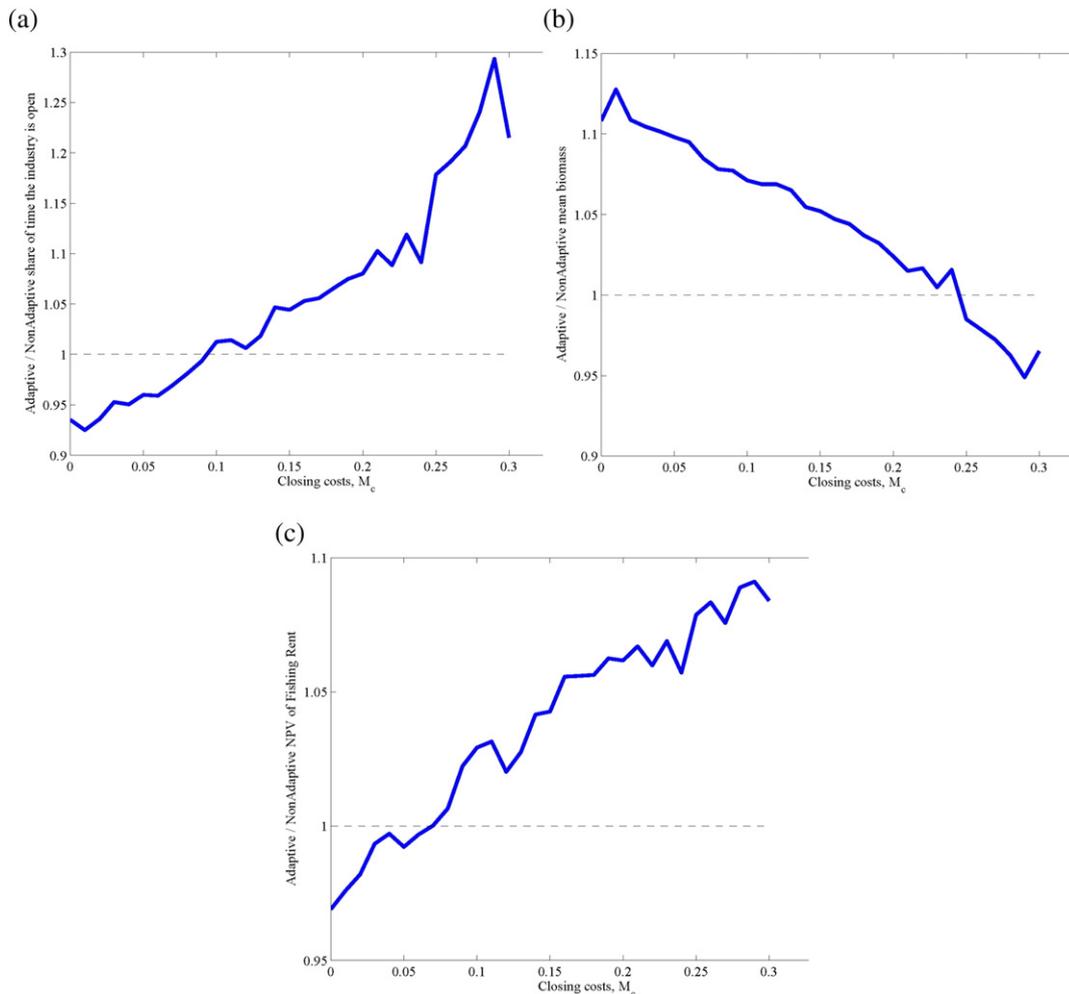

Fig. 4. Ratios for adaptive and non-adaptive policies for (a) the share of time the fishery is open, $\rho_n^{adaptive}/\rho_n^{non-adaptive}$, (b) resource biomass, $x_n^{adaptive}/x_n^{non-adaptive}$, and (c) resource rents, $\pi_n^{adaptive}/\pi_n^{non-adaptive}$, all as functions of the fixed cost of fishery closures.

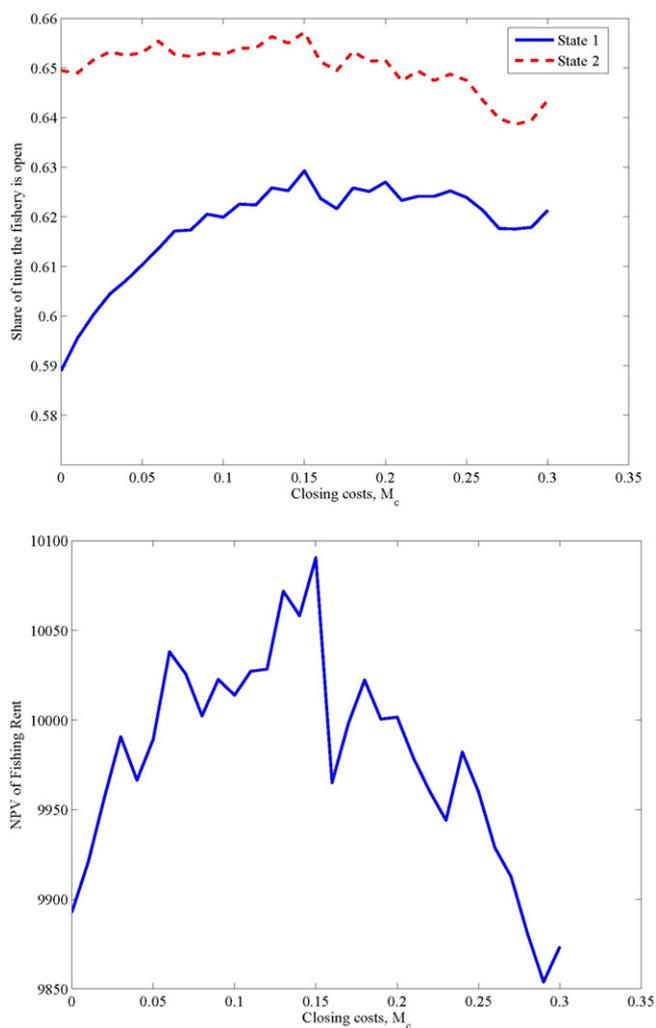**Fig. 6.** The net present value of rents as a function of the fixed cost of fishery closures for both the adaptive (solid blue line) and non-adaptive (red dashed line) management. Rents are in millions of dollars and are calculated at an average price of $52.44 per ton (real 2000 $) calculated by dividing the value of landings by landings downloaded from http://www.seaaroundus.org for the Humboldt Current Large Marine Ecosystem.

Fig. 5. The share of time the industry is open under each state (top) and the net present value of rents as a function of the fixed cost of fishery closures (bottom). Rents are in millions of dollars and are calculated at an average price of $52.44 per ton (real 2000 $) calculated by dividing the value of landings by landings downloaded from http://www.seaaroundus.org for the Humboldt Current Large Marine Ecosystem.

the persistence of the more productive state confers benefits. Whether or not this should induce resource managers to track the state of the system closely, however, depends on the cost of closure.

that the relative value of adaptation to changes in the resilience of a natural resource depends both on the fixed costs of the opening or closing of the resource, and on its resilience or persistence in different states. Where fixed costs are low the information guiding adaptation has negative value independent of the resilience of the natural resource system. As fixed costs rise, however, the marginal value of the additional information used in adaptive strategies increases monotonically, although it is sensitive to the persistence of different states. The less persistent the alternative states of the system, and the higher the fixed costs of opening and closing extraction, the more valuable is the information guiding an adaptive response. It follows that policies to provide information sufficient to allow adaptive responses have the potential to lead to welfare gains, and that this potential is greater the greater the fixed costs of closure.

As a final qualification we note that we do not model the determinants of extraction capacity. As a general proposition, we would expect that a change in the productivity of any natural resource system would induce a corresponding change in extraction capacity. For a given level of extraction capacity, however, adaptation to changes in the persistence of different states shows up as a change in the proportion of time that the resource is open. For a system that can exist in both more and less productive states, it follows that an increase in the persistence of the less productive state imposes costs, whereas an increase in
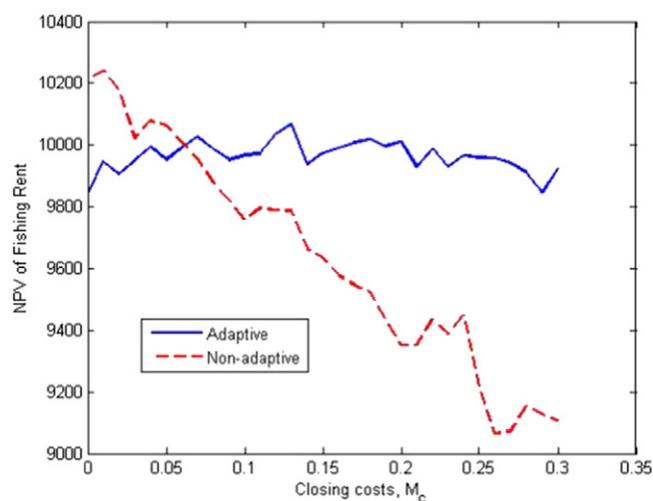
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