BIOECONOMIC ANALYSIS OF THE IMPACT OF OCEAN ACIDIFICATION ASSOCIATED WITH LOW RECRUITMENT OF *Isostichopus badionotus* AND IMPLICATIONS FOR ADAPTIVE FISHERY MANAGEMENT IN THE NORTH OF THE YUCATAN PENINSULA, MEXICO

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SUMMARY

The impact that ocean acidification (OA) could generate in the fishery of Isostichopus badionotus *at the north of the Yucatan Peninsula, Mexico, was analyzed by reducing the value of the α parameter of the Beverton-Holt recruitment function, in accordance with the acidification scenarios of the Intergovernmental Panel Panel on Climate Change (IPCC). The behavior of the stock and the resulting fishery were analyzed in a bioeconomic model structured by age, taking into account different market prices and fishing efforts. The results were compared in decision matrices that used the MiniMax and MaxiMin criteria to determine the management strategy that best reduced the impact of acidification. The largest stock reduction occurred during the first years of exploitation (B10/B0>B15/B0) and all the variables that were considered did stabilize with time, reaching bioeconomic equilibrium. The worst scenario for not considering acidification occurred with low market prices, while the increase in price decreased the exploitation rate. The recruitment reduction determined the maximum effort that should have been applied; under such conditions it is recommended to operate an effort of 137 boats, considering the best market price.*

Introduction

Climate change models integrate laboratory information in the form of population parameters that can be modified according to environmental trends (Doney *et al.,* 2009). A large part of these models reflects the effect that the condition exerts on survival (Seijo *et al.,* 2016); while others predict biomass change according to the stock structure and efficiency of recruitment (Hilborn and Walters, 1992). Tracking these changes allows linking the responses of individuals to the expected population patterns.

A group of organisms that is vulnerable to the effects of climate change and of global economic importance are sea cucumbers (Anderson *et al.,* 2010, Lundquist and Botsford 2011; Purcell *et al.,* 2016). Although the adult phases of these organisms have the physiological capacity and phenotypic plasticity needed to cope with the

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ANÁLISIS BIOECONÓMICO DEL IMPACTO DE LA ACIDIFICACIÓN DEL OCÉANO ASOCIADA AL BAJO RECLUTAMIENTO DE *Isostichopus badionotus* E IMPLICACIONES PARA EL MANEJO PESQUERO ADAPTATIVO EN EL NORTE DE LA PENÍNSULA DE YUCATÁN, MÉXICO

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RESUMEN

El impacto que la acidificación del océano podría generar en la pesquería de Isostichopus badionotus *en el norte de la península de Yucatán, México, fue analizado reduciendo el valor del parámetro α de la función de reclutamiento de Beverton-Holt, acorde con los escenarios de acidificación del Panel Intergubernamental sobre Cambio Climático (IPCC). El stock resultante y el comportamiento pesquero se analizaron en un modelo bioeconomico estructurado por edades, considerando diferentes precios de mercado y esfuerzos de pesca. Los resultados se compararon en matrices de decisión que emplearon criterios MiniMax y MaxiMin para determinar la estrategia de manejo que mejor redujo el impacto de acidificación. Los resultados indicaron que la mayor disminución de stock ocurrio en los primeros años de explotación (B10/B0>B15/B0) y que las variables de desempeño se estabilizaron con el tiempo, alcanzando equilibrios bioeconómicos. El peor escenario, por no considerar acidificación, ocurrió con bajos precios de mercado, en tanto que el incremento del precio disminuyó la tasa de explotación del recurso. La reducción del reclutamiento determinó el máximo esfuerzo que debió aplicarse; bajo estas condiciones es recomendable operar un esfuerzo de 137 botes para un precio de mercado de US$ 3,500 por tonelada.*

ANALISE BIOECONÓMICO DA ACIDIFICAÇÃO DO OCEANO ASSOCIADA AO BAIXO RECRUTAMENTO DE *Isostichopus badionotus* E IMPLICAÇÕES PARA A GESTÃO DA PESCA ADAPTATIVA NO NORTE DA PENÍNSULA DE YUCATÁN, MÉXICO

Enrique González Durán, Álvaro Hernández Flores e José Duarte Canul

RESUMO

O impacto que a acidificação poderia gerar na pesca de Isostichopus badionotus *no norte da Península de Yucatán, México, foi analisado reduzindo o valor do parâmetro α da função de recrutamento de Beverton-Holt, de acordo com os cenários de acidificação do painel Painel Intergovernamental sobre Mudanças Climáticas (IPCC). O comportamento do estoque e da pescaria resultante foram analisados em um modelo bioeconômico estruturado por idade, levando em consideração os diferentes preços de mercado e esforços de pesca. Os resultados foram comparados em matrizes de decisão que utilizaram os critérios MiniMax e MaxiMin para determinar a estratégia de gestão que melhor reduzisse o impacto da acidificação. A maior redução ocorreu nos primeiros anos de exploração (B10/B0>B15/B0), e todas as variáveis consideradas se estabilizaram com o tempo, atingindo o equilíbrio bioeconômico. O pior cenário para não considerar a acidificação ocorreu com o baixo mercado preços, enquanto o aumento do preço diminuiu a taxa de exploração. A redução de recrutamento determinou o esforço máximo que deveria ter sido aplicado. Sob tais condições, foi recomendado operar um esforço de 137 barcos, considerando o melhor preço de mercado.*

adverse conditions of climate change (Garcia-Arraras and Greenberg, 2001; Yang *et al.,* 2006; Yuan *et al.,* 2009; Zamora and Jeff, 2012; Gullian, 2013; Storey, 2015) larvae (if any) and the initial stages of benthic fixation are more vulnerable to changes in temperature and pH (Smiley, 1986; Asha and Muthiah, 2005; Brander, 2010; Morgan, 2008; Yuan *et al.,* 2015). Thus, these stages represent a bottleneck for the species dynamics (Asha and Muthiah, 2005; Hamel and Mercier, 2008; Yuan *et al.,* 2015; Koenigstein *et al.,* 2016).

In this paper we focus on the effects of pH on the recruitment of *Isostichopus badionotus*, a holothurian that is distributed in the northern coast of the Yucatán peninsula, which has been subject to fishing exploitation since 2012 (Hernández-Flores *et al.,* 2015). The effects of climate change were studied by modifying the recruitment function in an age-structured bioeconomic model (Anderson and Seijo, 2010) that used data from wild populations (Poot-Salazar *et al.,* 2014, Hernández-Flores *et al.,* 2018). Associated with the conditions of climate change and the modification of the recruitment, management strategies were defined to maximize the economic benefits and to compensate the adverse effects of climatic change.

Materials and Methods

Liability to pH

Published survival data for different species of holothurians and previous reports of gnomonic values of natural mortality (M) of *I. badionotus* indicate that the early stages of the life cycle, compared to the juvenile and adult phases, are more vulnerable to changing environment (Zacarias-Soto *et al.,* 2013; Gullian and Terrats, 2017; Romero-Gallardo *et al.,* 2018). This conclusion is congruent with the work that has been presented for larvae of different holothurian species (Hamel and Mercier, 1996; Asha and Muthiah, 2005; Morgan, 2008; Brander, 2010; Dupont *et al.,* 2010; Stumpp *et al.,* 2011; Zacarías *et al.,* 2013; Yuan *et al.,* 2015). Several studies conducted with sea cucumber larvae indicate that pH is a critical factor that can produce direct (Asha and Muthia, 2005; Hamel and Mercier, 2008; Yuan *et al.,* 2015) and indirect (Morgan, 2008; Brander, 2010) effects. Within the former, there are reductions in development, growth and survival in the presence of extreme alkaline values (pH 9.00), as well as malformations, disintegration and low survival (up to 49% less in *Holothuria spinifera*) by reduction of the optimum (pH 8.0) by 0.5 pH units (Asha and Muthia, 2005). Regarding the indirect effects, the quality and availability of food is a key factor for the survival of the early life stages of sea cucumbers (Brander, 2010).

Recruitment restriction

The dependence that the recruitment maintained with the biomass of the breeding population was calculated through the Beverton-Holt recruitment function. (Beverton y Holt, 1957):

$$R_t = \frac{\alpha SSB_{t-1}}{\beta + SSB_{t-1}}$$

where Rt: recuritmen in year t, SSBt–1: spawning stock biomass, α: máximum number of recruits, and β: spawning biomass that is required to produce a level of recruits equivalent to α/2. The parameter α was calculated from the biomass published by Hérnandez-Flores *et al.,* (2015), assuming equilibrium conditions, while the parameter β was calculated considering the period that it takes the stock to recover from 5 to 100% of virgin biomass (Poot-Salazar *et al.,* 2004). The impact that OA could have on larval mortality was incorporated by modifying α, using the values shown in Table I.

Bioeconomic model

We considered a sea cucumber population with asymptotic recruitment dependent on the size of the reproductive population and the average age specific of the females, in which the effects of mortality of the larval phases affect the settlement of the organisms; this population did not present a homogenous distribution of age classes, and has the same parameter of growth and natural mortality (r and M, respectively). The reproductive capacity of the females corresponds to that observed in laboratory specimens (Zacarías-Soto *et al.,* 2013) and is the sum of the biomasses of relevant ages, according to the recruitment function (Hilborn and Walters, 1992). It is assumed that in this population the weight of the individual is a function of its length, which changes with age, according to the von Bertalanfy's growth function (Poot-Salazar *et al.,* 2014). With regard to spatial allocation, it is assumed that the population allocates heterogeneously at different levels of K, implying that the density of the population grows until saturated and subsequently extends (Maunder and Deriso, 2013). Within the scope of its fishery, the age-specific catch is assumed to be derived from a catchability function that depends on the availability of the resource (Anderson and Seijo, 2010). It is also assumed that the number of boats constitutes the fishing effort and that its characteristics are kept constant over time with a selectivity that is established according to the magnitude of the catch, with a retention of 50 to 75% (Hernández-Flores *et al.,* 2015). An illustration of the essential elements of the model, including the mathematical expressions thereof, is presented in Figure 1.

TABLE I
VALUES OF α FOR THE RCP THAT DESCRIBE THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (RCP2.0, RCP6.0 AND RCP8.5)

Scenarios	α (individuals)	Rate of change (%)	pH
RCP2.6	55,724,807	0.0	8.0
RCP6.0	44,579,845	0.2	7.8
RCP8.5	33,434,884	0.4	7.6

*RCP: Representative concentration pathways.

Model parameters

Reported averages of age and growth of specimens collected in Celestún, Sisal and Progreso, all located in the northern coast of the Yucatan Peninsula, were used as model parameters (Poot-Salazar *et al.,* 2014). The parameters of the von Bertalanfy growth equation used were: K= 0.6 year^{1}, t_0= -0.50, L_∞= 31.6cm, with an exponential height-to-weight ratio (W_∞) of y= 0.14 (31.6 $^{2.6}$) (Poot-Salazar *et al.,* 2014). The maximum age was ten years, and in two years 50% maturation occurs, which coincides with the size of the first capture (22cm). The maximum biomass that can be registered in the 1702km^2 range of the resource was 93,000ton. It is estimated that an initial stock (206ton of breeding females) can produce 220,504,710 individuals at the end of the first reproductive cycle (Hernández-Flores *et al.,* 2015); these values were considered at the time of parameterizing the stock recruitment ratio, resulting in α= 55,724,807 and β= 1,618, considering a coefficient of Rikhter and Effanov (M) of 0.58 (Hernández-Flores *et al.,* 2018). The maximum allowed number of boats was 691 participating at an exit enter parameter of 0.000043 boats US\$$^{-1}$. Fixed cost, transfer cost unit, and other variable costs were 860, 75, and 40 US\$/day; and minimal price of the specie was 2000 US\$/ton.

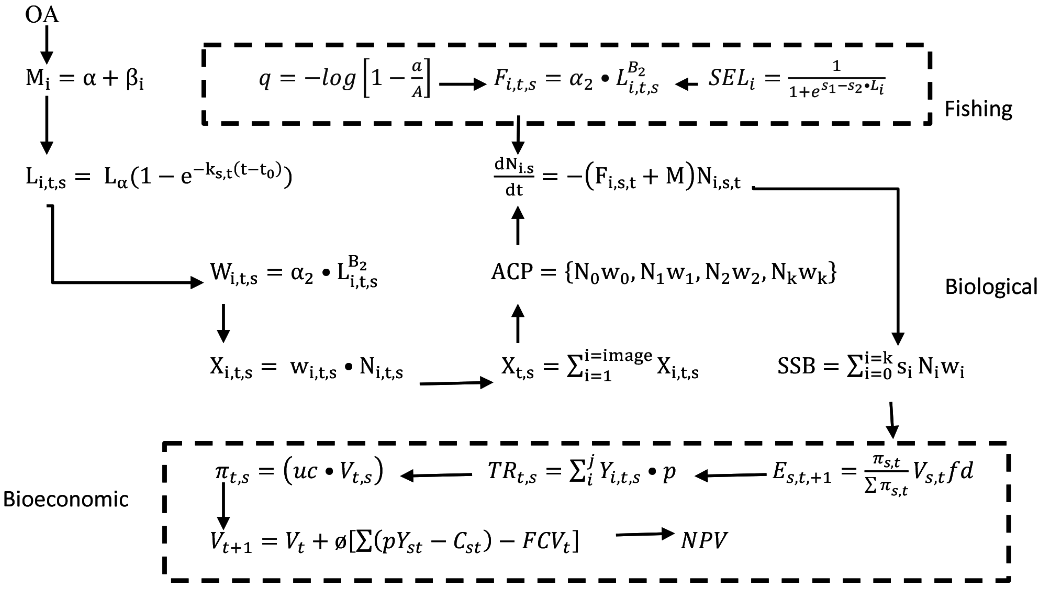

Figure 1. Schematic flow model of the equations that were employed in the construction of the bioeconomic model.

Age structure

Cohorts were followed over time in an age-structured model. Briefly, the number of individuals (Ni) across the different age classes (k) was plotted as a vector describing the passage of the population over time. The stock of spawning biomass (SSB) was determined considering the fertility coefficient (s_i) of each of the age classes. The changes in the dynamics of the fishing stock were determined following the modifications of the vector of the age class. The fishing mortality rate at a specific age was considered as the product of the effort and the catchability coefficient. In each year, the size of the age class zero was determined by recruitment and was related to the size of SSB. The size of any other age class was determined by the projection of the lower class by adding the effects of M and fishing mortality (F) (Anderson and Seijo 2010).

Bioeconomic impacts

The impact that price exerts on the bioeconomic balance depends on the costs, the rent and the abundance of the resource. All these were modified in turn by the restriction on recruitment which relates with OA. To determine this impact, three projections of fishing behavior were carried out using different market prices (US$ 2000, 2750 and 3500/ton). The model outputs were used to determine fishing effort intervals in which both spawning stock biomass and net present value (NPV) maintained positive values. Once these intervals were determined, the decision on the fishing effort to be applied at each of the scenarios were determined by the application of MiniMax and MaxiMin decision criteria.

The effects of climate change on NPV were analyzed in decision tables that integrated management strategies (related to fishing effort) and IPCC scenarios (related to the states of nature, θj) (Seijo *et al.*, 1998, 2016; Villanueva *et al.,* 2013). These tables present the results (r^{ij}) of each management strategy (rows) applied to each state of nature (columns) and their response in the NPV of the fishery (Eppen *et al.,* 2001) (Table II).

The loss of opportunities for each decision criterion was determined by comparing the NPVs that were obtained by combining fishing effort within each climate change scenario. These comparisons made it possible to identify the maximum NPV, which was then subtracted from the lowest values. The differences were used to generate an opportunity loss matrix that minimized the loss of opportunity according to the MiniMax criterion (Seijo *et al.,* 1998) (Table III).

The second decision criterion was the MiniMax, which included a regret matrix obtained from the payoff matrix. Again, the headings regret matrix were the states of nature in the columns and fishing mortality levels in the rows. The data were now obtained by selecting the highest average annual catch in each column and subtracting the outputs from that column (loss of opportunities). Therefore, each column contains a zero that corresponds to the maximum value. Then, the highest loss of opportunity was selected in each column of the regret matrix, and the final decision corresponds to the fishing mortality that produced the lowest loss of opportunities (Table III).

TABLE II
MATRIX FOR THE DEFINITION OF THE NINE STATES OF NATURE THAT RESULT FROM THE INTERACTION OF FISHING EFFORTS AND RCP

Decisions (D_i)	IPCC scenario (θj)		
	RCP2.6 (θ_1)	RCP6.0 (θ_2)	RCP8.5 (θ_3)
F_1	αF1θ1	αF1θ2	αF1θ3
F_2	αF2θ1	αF2θ2	αF2θ3
F_3	αF3θ1	αF3θ2	αF3θ3

TABLE III
DECISION-MAKING MATRIX WITH INTERACTION D_I AND θ_j AND ITS EFFECTS ON THE PERFORMANCE OF THE FISHING VARIABLE, THIS CASE NPV*

Decision (D_i)	IPCC scenarios (θj)			Criteria (MiniMax o MaxiMin)
	RCP2.6 (θ_1)	RCP6.0 (θ_2)	RCP8.5 (θ_3)	
F_1	$NPV_{1,1}$	$NPV_{1,2}$	$NPV_{1,3}$	C_1
F_2	$NPV_{2,1}$	$NPV_{2,2}$	$NPV_{2,3}$	C_2
F_3	$NPV_{3,1}$	$NPV_{3,2}$	$NPV_{3,3}$	C_i

*NPV: Net present value.

The performance variables that were used to measure the impact of OA (α) and F were recruitment, biomass, and fishing effort, as well as the proportion of biomass for a specific year (B_{10}) compared to the initial biomass (B_0), assuming B_0= K.

Results

The impacts of ocean acidification (OA) on the population structure of *I. badionotus* were determined using different values of the parameter α. These values were assigned according to the concentration trends representative of the IPCC (Table I). The responses were analyzed in an age-structured growth model. In each scenario of acidification, the price stimulated the fishing effort in terms of the gains that were obtained from the total catch volume. The increase in the adverse effects of OA (reduction of the value of α) decreased the profit margin regardless of prices (Table IV).

The number of vessels that maximize NPV according to the trends of representative concentration and prices is presented in Table IV. The best economic benefit under normal conditions without OA (θ_1) was obtained with US$ 3,500 using 182 boats. The reduction of α concentrated fishing effort from 167 to 115 boats with US$ 2,750 and from 182 to 137 boats with US$ 3,500. Under the conditions of RCP6.0 and RCP8.5, the maximum NPV was obtained at US$ 3,500 with 163 and 137 boats, respectively. The decision considered to define the number of boats that maximized the capture utility was obtained by applying the criteria MaxiMin and MiniMax (Tables V and VI). The marginal yields that were obtained by affecting the fishery with less recruitment and, consequently, higher operating costs, were low, regardless of price and fishing effort. Precautionarily, the fishing effort that could be applied in case maximum OA and presence of different market prices were: 95, 115 and 137 boats for US$ 2,000; 2,750 and 3,500; respectively (Table V).

The reduction of fishing effort from 182 to 137 was the strategy that most reduced losses in the presence of strong effects of OA (θ_3) and maximum resource price. Intermediate values of OA (θ_2) and intermediate prices allowed to operate with an effort in the range of 167 to 115 boats, with 147 being the effort that most reduced the marginal yield losses. Absence of OA (θ_1) in the presence of low price, allowed to operate in the range of 144 to 95 boats, being 144 the optimal effort (Table VI).

The management strategies identified by the MaxiMin and MiniMax criteria coincide in that a greater impact of OA, and increases the restriction of the number of participating boats, which explains that the best management option, given the increase in gravity of OA, is the strengthening of the precautionary approach.

The way in which the fishery could behave given current management conditions and considering possible OA scenarios, as well as the effect of market prices, shows that the

TABLE IV
MAXIMIZATION OF ECONOMIC BENEFITS ACCORDING TO MARKET PRICES AND OA EXPRESSED IN TERMS OF NUMBER OF BOATS AND (NPV IN 10^6 US $)

Price	RCP2.6	RCP6.0	RCP8.5
US$ 2,000	144 (57.2)	118 (39.8)	95 (23.8)
US$ 2,750	167 (88.5)	147 (63.5)	115 (39.8)
US$ 3,500	182 (121.4)	163 (88.1)	137 (56.6)

TABLE V
OUTPUTS OF THE MODEL (NPV IN 10^6 US$) THAT WERE OBTAINED BY RESTRICTING THE NUMBER OF BOATS PARTICIPATING IN THE FISHERY

a) US$ 2,000

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
95	54.4	39.2	23.8
118	56.5	39.8	23.3
144	57.2	39.3	21.9

b) US$ 2,750

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
115	85.3	62.3	39.8
147	88.1	63.4	38.9
167	88.5	63.1	37.7

c) US$ 3,500

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
137	118.9	87.3	56.6
163	121.0	88.1	56.0
182	121.4	87.7	54.9

The MaxiMin matrix shows three states of OA for each market prices.

TABLE VI
OPPORTUNITY LOSS MATRIX (10^6 US$) OF THE MINIMAX CRITERION FOR THREE STATES OF OA AND DIFFERENT MARKET PRICE

a) US$ 2,000

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
95	2.8	0.6	0
118	0.7	0	0.5
144	0	0.5	1.9

b) US$ 2,750

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
115	3.2	1.1	0
147	0.4	0	0.9
167	0	0.3	2.1

c) US$ 3,500

Maximum number of boats (D_i)	States of nature		
	θ_1: RCP2.6	θ_2: RCP6.0	θ_3: RCP8.5
137	2.5	0.8	0
163	0.4	0	0.6
182	0	0.4	1.7

increase in the restriction in α produces less spawning biomass and recruitment. Although the market price encourages participation in the fishery, the increase in adverse effects due to OA and consequently the reduction of exploitable biomass restricts fishing effort to maximize the economic benefits of the participants (Figure 2).

At all prices, fishing activity was greater during the first three years of exploitation; furthermore, between years 4 and 10, there were significant decreases in biomass, which significantly limits fishing effort. These effects were most evident when considering the impact of climate change. Subsequent monitoring shows that there were no major changes in fishing, indicating that activity remains profitable at a bioeconomic equilibrium, albeit at different levels of performance, even in adverse climate change scenarios (Figure 2).

The proportion of the initial biomass (B_0) that remains at B_{10}, shows that OA and fishing effort had no significant adverse effects on the conservation of the population, maintaining the B_{10}/B_0 ratio above 0.30 units (Figure 3a). Even when maintenance effects did not occur within the first ten years of exploitation, it might be possible that further exposure under similar condition could significantly affect the population (Figure 3b). Proportion of biomass at year 15 (B_{15})

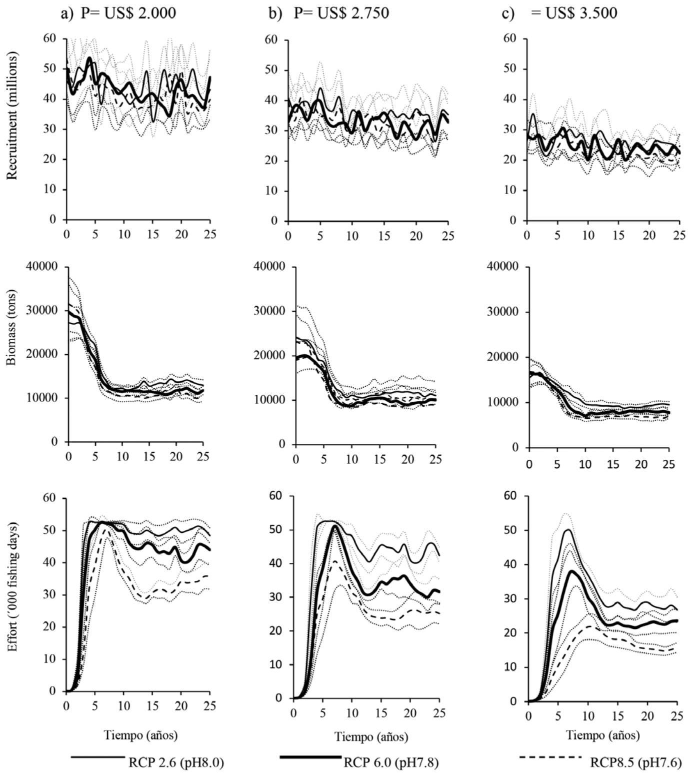

Figure 2. Behavior of the study variables (recruitment, biomass and effort) obtained at different prices (US$ 2,000; 2,750 and 3,500) in three different states of climate change (IPCC 2.6, 6.0 and 8.5).

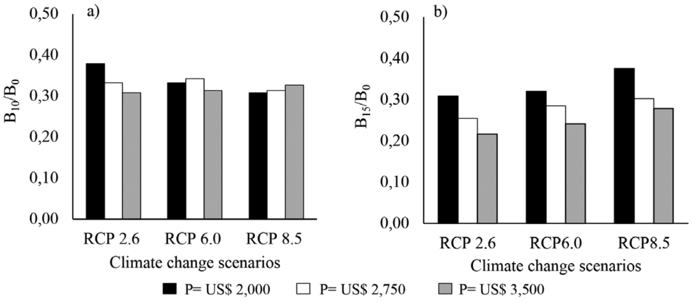

Figure 3. Fishery impact for the three scenarios of OA and prices: a) B10/B0; b) B15/B0.

with regard to year 0 (B_0), showed that extending the effect of OA in the long run and increasing the price of the product could reduce the resource (B15/B0 ratio) under 0.30 units.

Discussion

In this study, we focused directly on the effect that OA could exert on recruitment of *I. badionotus* by combining future scenarios (RCP) with probabilistic epistemic (α) prediction to build an approach that determine the possible consequences in a fishery. To avoid ambiguity, we presented a background that sustains evidence based on the possibility that such events could occur. The approach was further reinforced by decisions making under uncertainty conditions applying the criteria MiniMax and MaxiMin (Seijo *et al.,* 2016).

The decision to include the adverse effect of OA in the recruitment function is consistent with previous reports that exist for this and other marine invertebrate species, in which pH reduction significantly increased the harmful conditions for organisms and reduced survival (Tomanek *et al.,* 2011; Matozzo *et al.,* 2013; Hu *et al.,* 2015). Since some of these reports also indicated that such effects were greater in larvae than in juveniles and adults (Asha and Muthiah 2005, Morgan 2008, Yuan *et al.,* 2015) we conceived, in agreement with Hamel and Mercier (1996) and Zacarías-Soto *et al.,* (2013), that these stages of the life cycle represented a bottleneck for the organisms' survival.

Approaching the effects of climate change on recruitment is not new, and several studies that have included different methodological proposals have addressed the issue from an ecosystemic point of view. Previous work with barnacles (*Balanus glandula* and *Chthamalus dalli*) and oysters (*Mytilus* spp.) on the west coast of the USA, have shown that variation in large-scale climatic conditions such as El Niño-Southern Oscillation (ENSO), Decadal Oscillation (PDO) and the North Pacific Turnaround Oscillation (NPGO), and mean scale variations such as coastal upwelling, strongly affected the magnitude of the recruitment, accounting for up to 40% of the observed variance, representing a high explanatory power considering the great source of varition for recruitment (Menge *et al.,* 2011). Similar results were reported in the sense of recruitment affected by climates for the sardine *Sardinops sagax* by Galindo-Cortes *et al.,* (2010).

Although the prolific nature of the species could compensate for larval mortality (Zacarías-Soto *et al.,* 2013), the yield that was generated in terms of biomass exploitable under OA conditions was able to impact spawning stock biomass, producing differences that were reflected in lower yields in RCP8.5 as compared to RCP2.0; the effect of increasing recruitment constraint on performance reduction showed the above. Under these conditions, the best management option, given the increase in OA, is the strengthening of the precautionary approach; this allows to maximize income and offset the quasi-rent that are related to catch reduction (Anderson and Seijo 2010; González-Olivares and Flores 2015).

It should be noted that regardless of the OA condition and price, all monitoring indicators stabilized over time, suggesting that activity remains profitable because it achieves a bioeconomic equilibrium. This stability could be related to the incentives that fishermen need in order to maintain themselves in the fishing activity. In neither case, within the first ten years, the combination of price and climate change managed to collapse the resource, keeping B_{10}/B_0 index above 0.30. Nevertheless, when the effects were considered over a longer period of time, the drop of the ratio B15/B0 indicates that in the long run the combination of OA and price exert a more negative effect on the availability of the resource.

Conclusions

The decrease in catch, consistent with recruitment, dissipated rent and reduced fishing effort. These effects were greater as the price of the product increased. The best management strategy that compensates for the adverse effects of OA is the reduction of fishing effort.

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