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BIOECONOMICS OF TECHNOLOGICAL INTERDEPENDENCIES IN A SEQUENTIAL SHRIMP FISHERY: OPTIMAL SIZE OF THE INDUSTRIAL FLEET IN SOUTHERN GULF OF CALIFORNIA

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ABSTRACT. The bioeconomic sequential externalities in the white shrimp (*Litopenaeus vannamei*) fishery during 2014-2015 season in southern Sinaloa, Mexico, were analyzed by calculating the optimal size of the industrial fleet (trawlers) given the current oversized small-scale fleet (SSF: cayucos). For this purpose, we constructed a dynamic multi-fleet age-structured bioeconomic model with natural mortality-at-age and catchability-at-age. The distributed delay model was applied to simulate recruitment seasonality. The reproductive effect of seasonal sea surface temperature (SST) was also considered. The constant size of SSF was represented in *status quo* while reducing industrial fleet by -25%, -50% and by maximizing net present value "NPV" of industrial fleet. The model showed the technological interdependencies of two fleets competing for one species and their respective externalities. The *status quo* fishery showed a deteriorated biomass ($0.27 < 0.5_{MSY}$); overcapitalized fleet (especially for the SSF); fleets low NPV of resource rent, especially per fisherman per cayuco (~$1,150 USD per season). The access limitation of trawlers presented a progressive improvement in all bioeconomic variables, mainly on biomass (+27%) and NPV resource rent for trawlers (+908%). The SSF presented positive subtle externalities (6%). However, biomass was still below MSY (0.34) and the fishery trade-off showed a ~70% industrial fleet loss to overcome the negative externalities of the actual SSF status. Given the current conditions of the sequential shrimp fishery (i.e., overcapitalized, overexploited, difficulty to control SSF) the limitation of industrial effort to the area could be a viable strategy to improve the fishery bioeconomic performance. However, it is necessary to explore more management strategies that include the small-scale fishery to attained sustainable levels and higher profitability for users.

Keywords: small-scale fishery, sequential fishery management, Sinaloa, white shrimp, *Litopenaeus vannamei*.

Bioeconomía de las interdependencias tecnológicas en una pesquería secuencial de camarón: tamaño óptimo de la flota industrial en el sur del Golfo de California

RESUMEN. Se analizaron las externalidades secuenciales bioeconómicas en una pesquería de camarón blanco (*Litopenaeus vannamei*) durante la temporada 2014-2015 en el sur Sinaloa, evaluando el tamaño óptimo de la flota industrial (barcos) dada una flota de pequeña escala (SSF: cayucos) sobredimensionada. Para esto, se construyó un modelo bioeconómico estructurado por edades con mortalidad natural y capturabilidad variables por edad, y con un modelo de retraso distribuido se representó la estacionalidad del reclutamiento. Asimismo, para el área se incorporó el periodo reproductivo en el camarón relacionado con la temperatura superficial del mar (SST) estacional. El tamaño de SSF fue representando como el *status quo* y el tamaño de la flota industrial varío en -25%, -50% y maximizando el NPV sobre la flota industrial. El modelo mostró las interdependencias tecnológicas de dos flotas que compiten por una especie y sus respectivas externalidades. La pesquería bajo *status quo* mostró una biomasa sobreexplotada (0.27, <MSY); flotas sobrecapitalizadas, especialmente para SSF, reflejando una renta del recurso descontada (NPV) disminuida, especialmente por pescador por cayuco (~$1,150 dólares USD temporada^{-1}). La reducción industrial provocó una mejora progresiva de todas las variables bioeconómicas. La maximización del NPV de la flota industrial mostró una reducción del ~70% de barcos considerando las externalidades negativas causadas por el estado de la SSF. Esto resultó en beneficios máximos en la biomasa (+27%) y en NPV para los barcos (+908%) que permanecieran en la pesquería, incluyendo externalidades positivas menores para SSF (6%). Sin embargo, la pesquería aún no alcanzó niveles MSY (0.34). Dadas las condiciones actuales de la pesquería secuencial de camarón (sobrecapitalizada, sobrexplotada y dificultades controlando SSF), la limitación del esfuerzo industrial para mejorar el estado actual puede ser una solución viable para mejorar el despeño pesquero. Sin embargo, para alcanzar niveles sustentables se necesita explorar escenarios de manejo que incluyan a SSF.

Palabras clave: Pesquería de pesquera escala, manejo de pesquería secuencial, Sinaloa, camarón blanco, *Litopenaeus vannamei*.

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INTRODUCTION

The shrimp fishery worldwide provides food security, income, and employment in coastal communities, especially to livelihoods of fishermen in developing countries such as Asia and Latin America (Guillet, 2011; Pomeroy, 2012; CONAPESCA, 2018; Salas *et al*., 2019; FAO, 2020). Most shrimp fisheries are sequential in which technological interdependencies are generated between two fleets (a small-scale or artisanal fishery and an industrial fleet) when competing for a stock by capturing different components of the population structure (Seijo *et al*., 1998; Anderson & Seijo, 2010; Guillet, 2011). That is, the increase of the effective effort of the small-scale fleet will cause the decrease of adults, generating negative externalities to the industrial fleet. Similarly, the increase in industrial fishing effort decreases the spawning stock, which may decrease the recruitment of juveniles and pre-adults to the coastal area in subsequent periods, causing negative externalities to the artisanal or small-scale fleet. These complex characteristics make the management of sequential fishery challenging to authorities, particularly when regulating the size of the small-scale fleet (CONAPESCA, 2004; Ward *et al*., 2004; Guillet, 2011).

The most important fishery in México is the sequential shrimp fishery (CONAPESCA, 2018). It is based upon the commercial extraction of three penaeid shrimp (*Farfantepenaeus californiensis, Litopenaeus stylirostris* and *L. vannamei*), where an artisanal fleet capture juveniles with cast nets and cayucos/canoes in costal lagoons and shallow bays, while industrial boats or trawlers capture adults in marine waters (INAPESCA, 2016). The relative importance of the capture per species varies spatially and per fleet, where the industrial fishery is a multispecies fishery and the artisanal fisheries depend mostly on the white shrimp (from southern Sinaloa to Chiapas) or blue shrimp (from central Sinaloa to the upper Gulf of California) (INAPESCA, 2013). As a specie with a high adaptive plasticity (Leal-Gaxiola *et al*., 2001), its biology is closely related to environmental conditions, presenting for subtropical regions two heterogeneous peaks of reproduction per year (i.e. main peak in summer and secondary in autumn; Castro-Ortiz & Lluch-Belda, 2008). In addition, the intrinsic characteristics of these crustaceans, such as their high fecundity and short life cycle (García & LeReste 1986), could provide them with short-term population responses and high resilience to variation in fishing and natural mortality.

Management of the fishery in the country is dictated by General Law of Sustainable Fishing and Aquaculture (LGPAS, by its Spanish acronym), the Official Mexican Norm (NOM-002-SAG/PESC-2013) and the National Fishing Chart (DOF, 2018), and it is based on 1) access rights by a commercial permit, although, the LGPAS allows any person living in the Mexican coast to fish any species under the status of domestic consumption fishery creating, by default, an open access situation; 2) fishing gear regulations (mesh size); 3) zonal capture restrictions; and 4) seasonal closures to protect growth and reproduction between March and September. The fishery Target Reference Point (TRP) was established at the Maximum Sustainable Yield (MSY), where a determined level of biomass and effort will produce the maximum surplus yield (CONAPESCA, 2004).

Reported stock assessments for the Pacific penaeid stock indicates a fully exploited fishery (National Fishing Chart, DOF 11/06/2018). However, there are local areas reporting overfishing status and deteriorated shrimp stocks in Sonora, Sinaloa and Tehuatepec (Madrid-Vera *et al*., 2012; INAPESCA, 2016; Cervantes-Hernández *et al*., 2008; Rivera-Velázquez *et al*., 2009; Ramos-Cruz, 2013). In the case of the overexploited white shrimp, the main conflicts are caused by: a) illegal fishing during closure; b) overcapitalization of both fleets; c) weak governance; and d) limitations on fishery surveillance and enforcement for regulation, especially for the small-scale fleet. However, industrial fleet management is more efficient, each trawler is tracked by a vessel monitoring system (VMS) during the season (INAPESCA, 2016). Additionally, the industrial effort has been reduced by 54% since 2004 (from 1,674 to 755 trawlers in 2018: CONAPESCA, 2018) through the program of voluntary withdrawal of boats or buybacks, offering $65,000 USD per trawler (DOF 27/02/2019, taking current USD exchange rate to Mexican peso). Efforts have been made to regulate the fishing effort of the entire fishery, however, the artisanal fishery component still represents the greatest national and global challenge in terms of its management, as a result of its low control capacity due to a large number of fishers and landing zones, social complexities and limited institutional capacities (Gillett, 2008; Salas *et al*., 2019).

The bioeconomic analysis allows to assess the externalities produced by the technological interdependences of the sequential fisheries, exploring several management scenarios to achieve optimum performance levels over time in resource conservation, resource rent, and food security (Seijo *et al*., 1997). Unfortunately, most Mexican shrimp fishery models do not address the fundamental structure of sequential fishery analysis: technological interdependencies and/or age-structure models. Their main focus is on industrial fleet fishing assessment using dynamic biomass models under constant natural mortality and/or catchability assumptions (Industrial fleet: Morales-Bojórquez *et al*., 2001; Medina & Soto, 2003; Cervantes-Hernández *et al*., 2006; García-Juárez *et al*., 2009; Meráz-Sánchez *et al*., 2013; García-Juárez *et al*., 2014; Small scale fleet: Rivera-Velazquez *et al*., 2009; Madrid-Vera *et al*., 2012).

As such, this study aims to represent the seasonal bioeconomic behavior of the white shrimp sequential fishery in southern Sinaloa for the 2014-2015 season using an age-structured bioeconomic model with two heterogenous fleets competing for the same resource and harvesting different age components of the stock (i.e. technological interdependencies). Additionally, we will assess the stock dynamics with a constant-overcapitalized artisanal effort and establishing management regulation scenarios based on a progressive reduction (from 25 to 50% from the total) and the maximization of the net present value of the of the industrial fleet, analyzing the bioeconomic results of the outputs. The rationale of the proposal is based on increasing the welfare (measured in catches and income) of the shrimp fishery by reducing the industrial effort under an overcapitalized, constant, and an apparent unregulated artisanal effort. This result possible due to institutional mechanisms in place (i.e., buybacks programs) that allow for the industrial effort to be reduced. We intend to explore levels of industrial fleet reduction like those achieved by the buyback program, i.e. 25%, then reduce the effort further to 50%, and finally explore what level of industrial effort maximizes the resource rent over time for the area. These results will lead to an effective proposal to improve the shrimp fishery bioeconomic performance given its *status quo* condition.

MATERIAL AND METHODS

Study site

The study area is located between Mazatlán (23°14' 29"N 106°24'35"W) and Teacapán (22°30'40"N y 105°47'44"W), designated as zone 40 by the National Fisheries Institute (INP). This area includes the lagoon systems including the marine system of southern Sinaloa, encompassing the fishing communities of Mazatlán, Huizache and Caimanero, Chametla, Las Cabras, Teacapán and Palmilla (Fig. 1).

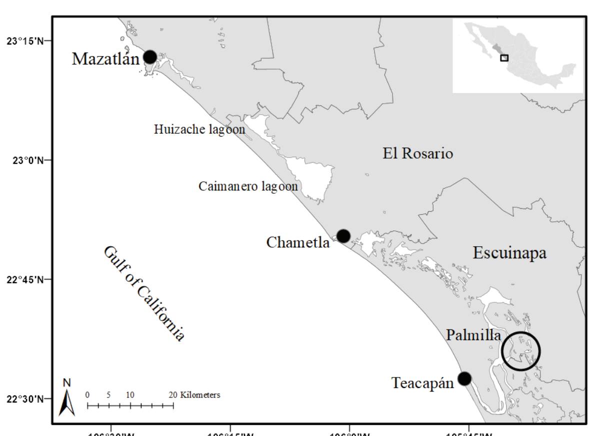


Figure 1 - Study area in southern Sinaloa.

Sea surface temperature (SST) in the region of interest showed a seasonal cycle (Fig. 2) with an average minimum SST in March (22.37 ± 0.908)°C and maximum SST of (29.24 ± 0.773)°C during August-September. The SST was obtained from the Extended Reconstructed Sea Surface Temperature (ERSST) data base (V5; Smith *et al*., 2003; Huang *et al*., 2017). Reproduction and recruitment processes were associated to seasonal cycled of SST (Castro-Ortíz & Lluch-Belda 2008; Aragón-Noriega *et al*., 2012).

Data bases

For the 2014-15 shrimp fishing season, fishing efforts were calculated for the small-scale and industrial fleet that harvested white shrimp in southern Sinaloa (Table 1). Five information sources were consulted: 1) fishing logbooks and interviews with 16 fishing cooperative organizations plus one owner of 16 industrial trawlers in the port of Mazatlán; 2) technical reports on species size structure in lagoons (Muñoz-Rubi *et al*., 2012); 3) species size structure of industrial catch data, as obtained from the shrimp processing plant "Mexican Shrimp Paradise" in the port of Mazatlán; 4) SADER (formerly SAGARPA)-CONAPESCA official landings database; and 5) satellite database of VMS of industrial trawlers.

Age-structured bioeconomic model

An age-structured model was used for the white shrimp fishery with two interannual recruitment events modeled using a distributed delay model developed by Manetsch (1976). Catchability-at-age was calculated independently for each fleet and natural mortality-at-age was obtained as explained in a previous study by Aranceta *et al*., (2016). The age-structured bioeconomic model consists of three sub-models described below:

Biological sub-model

Age, length and weight were taken from the von Bertalanffy growth function estimate of Chávez (1971) and modified in this study using field observations and maximum size observed. To estimate length-at-age and weight-at-length we used the following equations:

$$L_i = L_\infty * (1-\exp^{-(k*(t_i-t_0))}) \qquad \text{eq. 1}$$

$$W_i = aL^b{}_i \qquad \text{eq. 2}$$

Where L_i is length-at-age t; L_∞ is the maximum length; k is the growth rate coefficient; and t_0 is an adjusting parameter to represent the lagoon age recruitment [i.e. postlarvae ranging sizes of 5 -11mm; Gutiérrez-Venegas (1980)]. W_i is the weight-at-age; is the scaling constant; and b is the growth parameter. The bioeconomic parameters used in this study are included in Table 2.

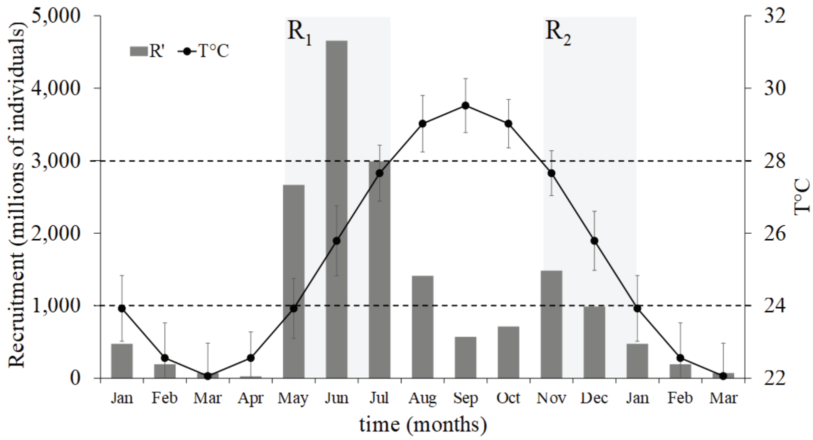


Figure 2 – Seasonal breeding and recruitment peaks (R_1 and R_2) for the white shrimp *Litopenaeus vannamei* in relation to the seasonal sea surface temperature (optimum breeding SST between 24-28°C) in Southern Sinaloa.

The dynamic of the age cohort survival was calculated using the equation (Anderson & Seijo, 2010):

$$N_{i+1,t+1}=N_{i,t} * \exp^{-(M_i+\Sigma F_{i,t,m})} \qquad \text{eq. 3}$$

Where $N_{i,t}$ is the number of individuals of age i in time t; M_i is the natural mortality of individuals of age i; and F is the fishing mortality (as explained below) caused on individuals of age i in time t by the small-scale and industrial fleets (m).

The reproductive effect of the seasonal sea surface temperature (SST) was included on the model as described in Figure 2. The observed reproductive period of the area presents two seasonal peaks (spring and autumn) related to the variability of the SST, where the optimal reproductive SST is between 24-28°C (Castro-Ortiz & Lluch-Belda, 2009). The first peak is responsible for recruitment to the fishery, and their surviving adults during the fishing season will generate the autumn's second reproduc-

Table 1 – Effort and catch variables for the a) industrial and b) small-scale fleet for the white shrimp fishery during the 2014-2015 season in southern Sinaloa.

a) Industrial fleet	Number of trawlers[1]	Effective fishing days[1] (per trawler)	Average CPUE per trawler[1] (ton/day)	Total industrial fleet catch[2] (ton/season)
October	72	17	0.080	97.33
November	29	21	0.047	22.87
December	43	28	0.027	25.64
January	74	23	0.042	34.36
February	70	31	0.044	65.55
March	10	22	0.064	12.26
Total	74max	142		258

b) Small scale fleet	Number of cayucos[2]	Daily cast net throws per cayuco[3]	Effective fishing days[2] (per cayuco)	Average CPUE per cayuco[4] (ton/day)	Total artisanal fleet catch[2] (ton/season)	Total artisanal fleet catch[6] (ton/season)
September	2000	50	23	0.017	424.53	654.53
October	1000	150	25	0.015	183.47	308.47
November	1000	67	25	0.0043	40.98	165.98
December	1000	74	25	0.00096	30.28	155.28
Total	2000max		98		679.26	1,284.26

[1]CONAPESCA and VMS database; [2]CONAPESCA; [3]Muñoz-Rubi *et al*. 2012; [4]Fishing logbooks; [6]CONAPESCA + chole (Chole = is an extra 5kg of shrimp per cayuco per day granted by the fishing cooperative, used as food or for income).

Table 2 – Bioeconomic parameters for the multi-fleet age-structured bioeconomic model for the white shrimp (*Litopenaeus vannamei*) fishery during the 2014-2015 season in southern Sinaloa.

Parameters	Value	Units	Reference
k	0.230	month -1	This study
W_∞	107.481	g	This study
L_∞	230.0	mm	This study
t_0	- 0.414	-	This study
a parameter L-W	2.47E-07	-	This study
b parameter L-W	3.657	-	This study
Beverton – Holt parameter α_{R_1}	5.85E+10	individuals	This study
Beverton – Holt parameter β_{R_1}	548	tons	This study
Beverton – Holt parameter α_{R_2}	2.0E+10	individuals	This study
Beverton – Holt parameter β_{R_2}	2,824	tons	This study
Length at 50% gear retention – small scale	114.47	mm	Lluch 1974
Length at 75% gear retention – small scale	124.14	mm	Lluch 1974
Parameter selectivity equation – small scale (s_1)	13.01	-	Lluch 1974
Parameter selectivity equation – small scale (s_2)	0.11	-	Lluch 1974
Length at 50% gear retention – industrial	139.68	mm	Lluch 1974
Length at 75% gear retention – industrial	149.35	mm	Lluch 1974
Parameter selectivity equation – industrial (s_1)	15.87	-	Lluch 1974
Parameter selectivity equation – industrial (s_2)	0.11	-	Lluch 1974
Price function parameter *a*	34,458	USD	This study
Price function parameter *b*	2.14	-	This study
Price function parameter *c*	-0.30	-	This study
Discount rate δ	0.0042	month -1	
D average maturation period	4		This study
g order of distributed delay	3		This study

*Costs per fleet are included in Table 3.

tive peak, producing the spawning stock biomass (SSB) of the spring peak. The fertilized eggs hatch after 14h and the larvae take 10-14 days to be recruited to the coastal area (Aragón-Noriega & Alcántara-Razo, 2005), where they are considered of age/month .

To represent the latter, two main recruitment periods for *L. vannamei* were adjusted to the model: a spring-summer peak in May-June (R_1 or recruitment 1) and autumn-winter peak in October-November (R_2 or recruitment 2). R_1 was the result of the SSB survivors of November - January and R_2 from the SSB survivors of May - July. From the above, two Beverton-Holt (1957) recruitment functions were generated for each breeding period:

$$R_1 = \frac{\left(\sum_{t_{11}}^{t_{13}} SSB\right) * \alpha_1}{\left(\sum_{t_{11}}^{t_{13}} SSB\right) + \beta_1} \quad \text{eq. 4a}$$

$$R_2 = \frac{\left(\sum_{t_5}^{t_7} SSB\right) * \alpha_2}{\left(\sum_{t_5}^{t_7} SSB\right) + \beta_2} \quad \text{eq. 4b}$$

Where α is the maximum possible number of recruits and β is the SSB needed to produce (on average) α/2 recruits. t represents the number of month where t13 is January of year 2.

The recruitment obtained from the Beverton-Holt function was distributed in the remaining months using the distributed delay model (Manetsch, 1976). The distributed delay model has been applied to fisheries to distribute recruitment of individuals seasonally, in populations of short-lived species (e.g. octopus, shrimp) where modelling recruitment seasonality is essential for properly managed the fishery (Seijo *et al*. 1994; 1998; Anderson and Seijo, 2010; Duarte *et al*., 2018). Once total recruitment is calculated, individuals are distributed over time using a gamma distribution with the parameters that best fit fishery observations. This model is based on the Erlang or Gamma probabilistic density function, described (Anderson & Seijo, 2010):

$$\frac{dR_1}{dt} = \frac{g}{D}[pl_{i,t}-R_{1,t}] \qquad \text{eq. 5a}$$

$$\frac{dR_2}{dt} = \frac{g}{D}[R_{i,t}-R_{2,t}] \qquad \text{eq. 5b}$$

$$\cdots \qquad \cdots$$

$$\frac{dR_g}{dt} = \frac{g}{D}[R_{g-i,t}-R_{g,t}] \qquad \text{eq. 5c}$$

Where g (an integer) specifies the member of the family of Erlang functions; D is the average development time; $pl_{i,t}$ is postlarvae recruiting to the area, $R_{g,t}$ is recruits to age 1, $R_{1,t}$, $R_{2,t}$...$R_{g,t}$ are the intermediate rates of the delay process used to represent the distribution of seasonal recruitment.

Solving ec. 5 using Euler numerical integration:

$$R_{1,t+dt} = R_{1,t} + DT[\frac{g}{D}(pl_{i,t}-R_{1,t})] \qquad \text{eq. 6a}$$

$$R_{2,t+dt} = R_{2,t} + DT[\frac{g}{D}(R_{1,t}-R_{2,t})] \qquad \text{eq. 6b}$$

$$\cdots \qquad \cdots$$

$$R_{g,t+dt} = R_{g,t} + DT[\frac{g}{D}(R_{g-i,t}-R_{g,t})] \qquad \text{eq. 6c}$$

The value of the initial recruitment in was obtained from the result of the distributed recruitment delay function ($R_{g,t+dt}$). The initial recruitment values per peak were adjusted to the observed catch for both fleets. Then, a Beverton-Holt recruitment function was adjusted per seasonal reproductive peak using the GRG Nonlinear solving method implemented in SOLVER with EXCEL 2016 © software.

Technological sub-model

The fishing mortality of fleet (F_m) was estimated as:

$$F_m = q_{i,t} s_i E_{i,t} \qquad \text{eq. 7}$$

Where $q_{i,t}$ is the catchability-at-age i in time t (months); s_i selectivity for age i; $E_{i,t}$ is the units of effort (explained below) of the fleet (F_m) in time t.

The catchability-at-age per fleet was estimated following the methodology for commercial penaeid shrimps in Aranceta *et al*., (2020) and using the computational algorithm by Martínez-Aguilar *et al*., (1999). Catchability-at-age was estimated for the industrial fleet using as units effective fishing day per trawler (Table 1a), and for the artisanal fleet in throws per day per cayuco. The throws per day (Table 1b) were estimated from the shrimp population evaluation of the Sinaloa southern lagoons technical report by Muñoz-Rubí *et al*., (2012).

Selectivity at age (i) of the fleet (m) was calculated (Sparre & Venema, 1998):

$$sel_{m,i} = \frac{1}{1+e^{(s1_m - s2_m * L)}} \qquad \text{eq. 8}$$

The unit of effort for the industrial fleet is fishing days per trawler and for the artisanal fleet is fishing days per cayuco (Table 1a, 1b).

The calculation of harvest by age class for *L. vannamei* per fleet follows Baranov (1918) equation:

$$Y_{i,t,m} = \left(\frac{F_{i,t,m}}{\sum F_{i,t,m} + M_i}\right)[1-e^{(-(\sum F_{i,t,m}+M_i))}]N_{i,t} \qquad \text{eq. 9}$$

Where $F_{i,t,m}$ is the fishing mortality of fleet m, M_i is the natural mortality at age i and $N_{i,t}$ is the population size in individuals at time t and age i.

The catch structure for the industrial fleet was estimated using the records of a processing plant in Mazatlán (Mexican Shrimp Paradise) during the complete 2014-2015 fishing season. The catch structure for the artisanal fleet was estimated from the technical report by Muñoz-Rubi *et al*., (2012). The estimated catch structure was adjusted to the total catch reported by the landings database for each fleet by SADER-CONAPESCA as an input to the bioeconomic model.

Economic sub-model

Costs and prices per fleet

The capital, variable, fixed and opportunity costs by fleet are described in Table 3. The USD exchange rate in 2014-2015 was ~$14.31 MX pesos. The opportunity cost used for the industrial fleet was estimated for the fishing season (142 days) and valued in $90,800 USD (DOF 27/02/2019) in relation to the buyback program. This was based on the fact that most of the trawlers (85%) were >20 years old and former 50% of the pacific industrial fleet used the buyback program (INP, 2000).

Prices for whole shrimp at age per ton for the small-scale fleet were established in $1,398 USD/ton for age 1: $2,795 USD/ton for age 2; and $5,590 USD/ton for ages 3-5. For the industrial fleet the prices per ton of tails were obtained from an official price list used by the shrimp processing plants in the 2014-2015 season. This required applying a conversion factor of 0.6 to the industrial yield in total weight per age.

A price per age per ton function was generated that significantly adjusted for white shrimp industrial tail prices:

Table 3 – Total costs per fleet for the white shrimp fishery during the 2014-2015 season in southern Sinaloa.

	Small scale fleet		Industrial fleet		
	Units	Cost (USD)	Units	Cost (USD)	
Capital costs	Cayuco boat	$1,397	Industrial trawler value from the buy-back program	$90,845	
	2 cast nets	$279			
	Total	$1,677	Total	$90,845	
Variable costs (VC)	Equipment repair cost	$279		Trip 1	Trip+1
	Cayuco equipment	$275	Total variable cost	$60,474 (%)	$36,483 (%)
	Food expenses	$373	Fuel and oil cost	35%	55%
	Total[1]	$928	Personnel cost	20%	23%
			General maintenance cost	17%	4%
			6 net repair cost	9%	1%
			Consumable materials	8%	4%
			Food purchase	3%	5%
			Other costs	8%	8%
Fixed costs (FC)	NA			Trip 1	Trip+1
			Total fixed cost	$102,700 (%)	$46,000 (%)
			Ship Hull maintenance	54%	0%
			Port rights	4%	4%
			Social security (IMSS & INFONAVIT)	4%	9%
			Administration costs	29%	65%
			Vessel and personnel insurance	9%	21%
Opportunity Costs (OC)	Annual bank rate of 5% of the capital costs per cayuco	$83	Annual bank rate of 5% of the capital costs per trawler[2]	$4,542	

[1] based on the fishing season of 98 effective days from September to December; [2] based on the fishing season of 142 effective days from October to March

$$P_i = \frac{a}{(1+\exp^{(b+c+i)})} \qquad \text{eq. 10}$$

where a represents the price per ton limit of $34,458 USD, b and c are adjustment parameters.

Bycatch revenues

Bycatch revenues were calculated for the j-bycatch species reported in the landings per trip during the 2014-2015 fishing season on a sample of 16 trawlers. The prices were obtained from interviews with ship owners. The units were estimated in bycatch ton/day and converted to bycatch revenues USD/day as shown in table 4. Thus, the average bycatch revenues for each species were calculated for each month of the fishing season, varying in function of the industrial fleet's fishing days:

$$I_t = \left(\sum_{j=1}^{j=n} X_{j,t} P_j \right) d_t \qquad \text{eq. 11}$$

Where I_t is the bycatch revenue per month; is the biomass in tons of the -bycatch species of the month ; is the price per ton of the -bycatch species; and are the effective fishing days per month of the industrial fleet.

Resource rent

Total revenues, total costs and resource rent for each fleet were calculated using the following formulas:

$$TR_{m,t} = \sum_{i=1}^{i=T} P_{i,m} Y_{i,t,m} + l_t \qquad \text{eq. 12}$$

$$TC_{m,t} = VC_{t,m} + FC_m + OC_m \qquad \text{eq. 13}$$

$$RR_{m,t} = TR_{m,t,} - TC_{m,t} \qquad \text{eq. 14}$$

Where the total revenues ($TR_{m,t}$) per fleet (m) are the sum of the product of the age class-specific price ($P_{i,m}$) and the age-specific yield $Y_{i,t,m}$ in time t plus the bycatch revenues (l_t) in time t. The industrial yield was represented in total weight and was converted to tail weight by applying a conversion factor of 0.6. Total costs ($TC_{m,t}$) per fleet (m) are the sum of all cost in time t; and the resource rent per fleet (m) is the subtraction of $TR_{m,t}$ and $TC_{m,t}$.

The net present value of resource rent (NPV) was estimated for a period of 5 years, based on the resource intrinsic characteristics (i.e. high fecundity and short life cycle), using the equation:

$$NPV_m = \sum_{t=0}^{t=T} \frac{RR_{m,t}}{(1+\delta)^t} \qquad \text{eq. 15}$$

Where NPV_m is the resource rent of the fleet (m) at time t discounted by a monthly discount rate (δ) in a given period of time t.

Model validation

For the validation of the sequential bioeconomic model for each fleet (i.e. cayucos and trawlers),

Table 4 – Daily bycatch revenues (USD/ton) per month for the industrial fleet in the white shrimp fishery (*Litopenaeus vannamei*) during the 2014-2015 season in southern Sinaloa.

Species	Common name	Oct	Nov	Dec	Jan	Feb	Mar
Farfantepenaus californiensis	Brown shrimp	$2,324.1	$1,380.1	$1,039.7	$365.1	$441.2	$557.9
Litopenaues stylirostris	Blue shrimp	$329.1	$109.6	$440.8	$34.2	$123.7	$468.0
Rimapenaeus pacificus	Botalón shrimp	$1.8	$0.2	$1.70	$1.49	-	-
Farfantepenaeus brevirostris	Crystal shrimp	-	-	$17.4	$15.2	-	$113.8
Lutjanus peru	Huachinango	$38.3	$40.7	$27.5	$19.4	$10.9	$100.7
Umbrina sp.	Berrugata	$121.2	$135.1	$121.1	$113.8	$72.7	$73.12
Cephalopoda	Squid	$0.3	$0.4	$2.8	$2.5	$0.3	$1.1
Caranx sp.	Jack	-	-	$7.0	$6.2	-	-
Haemulidae	Burro	-	-	-	$5.1	$6.0	$16.2
	Mix fishes	$28.3	-	-	-	-	-
Total		$190	$176	$178	$164	$90	$191

the observed and estimated CPUE were used as performance variables, applying the parametric tests of the correlation coefficient (r) and Pearson's coefficient of determination (R^2). Likewise, the nonparametric test of the Theil statistic (U) was also employed, which has an interval of values between [0,1] that measures the degree of discrepancy between the observed and estimated data, where values 1 suggest that the descriptive power of the function is approximated by randomness. This estimator is related to the root mean square error (RMSE), which is disaggregated into three components: mean, variance and covariance (Barlas, 1989; Loría, 2007; Pindyck & Rubinfeld, 1991; Power, 1993). A U-value of less than 0.2 is considered acceptable to validate the predictive power of the model (Roff, 1983; and Power, 1993).

Bioeconomic scenarios

Management scenarios were generated based in the reduction of the number of *status quo* industrial vessels of the fishery for the 2014-2015 season. Due to the historical reported reduction in the industrial fleet (i.e. 36% since 2004: INAPESCA, 2016), we are exploring the fishery bioeconomic effects applying a reduction in the maximum allowable number of trawlers in the study area by 25% and 50%. Alternatively, based in other international fisheries management target points applied in crustacea, such as the Maximum Economic Yield, we will explore the maximization of the NPV exclusively for the industrial effort. The small-scale fleet size was in *status quo* for every management scenario (Table 1b), representing their current management status, with no effective management measures to restrict their entry into the fishery and with a constant fishing effort over time. Given that shrimp fishery management uses the maximum sustainable yield (MSY) as a reference point (INAPESCA, 2016), this was used as a target reference point for each management strategy and calculated as half of the unexploited or virgin biomass (Seijo *et al*., 1998):

$$X_{MSY} = \frac{K}{2} \qquad \text{eq. 16}$$

Where X_{MSY} is the total biomass at MSY, K represents the carrying capacity of the environment where the largest biomass can be achieved taken from a no-fishing scenario.

RESULTS

Model output

The age structure of the catch during the shrimp fishing season 2014-2015 showed individuals from age 1 to 12. The segregation of the resource according to their maturity was observed in the age composition of the catch per fleet. The small-scale fleet harvested young individuals from age 1 to 5 and the industrial fleet caught adult individuals from age 4 to 12 (Fig. 3 and Fig. 6).

High catchability values were observed in the small-scale fleet at the beginning of the fishing season over the migration ages (age 4 and 5), with and a subsequent decrease during the following season (Fig. 3). Similarly, for the industrial fleet, high catchability values were recorded on the oldest age component at the beginning of the season (ages 9 to12). Catchability coefficient values were higher in the industrial fleet (Fig. 3).

The age-structure model adequately represented the estimated catch per unit effort (CPUE) values, validated through the observed CPUE values (Fig. 4). This was confirmed by the observed r and R^2 values approaching 1 and by the values of the U-statistic less than 0.2 for both fleets, which corresponds to a high predictive power of the model.

The estimated recruitment within the biological sub-model were consistent with the observed reproduction periods in spring-summer (R_1) and autumn-winter (R_2) (Fig. 2). Both in relation with the optimum SST for reproduction in southern Sinaloa.

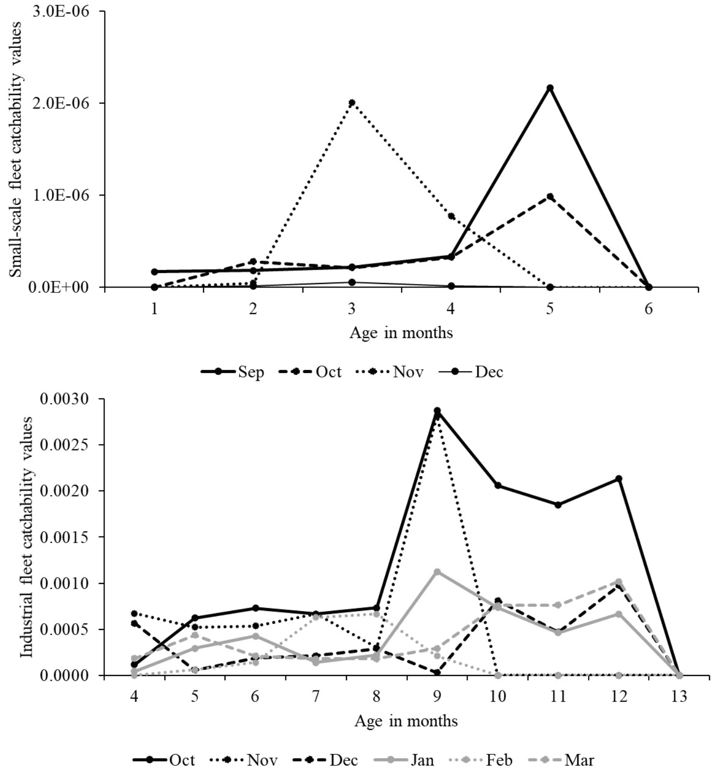
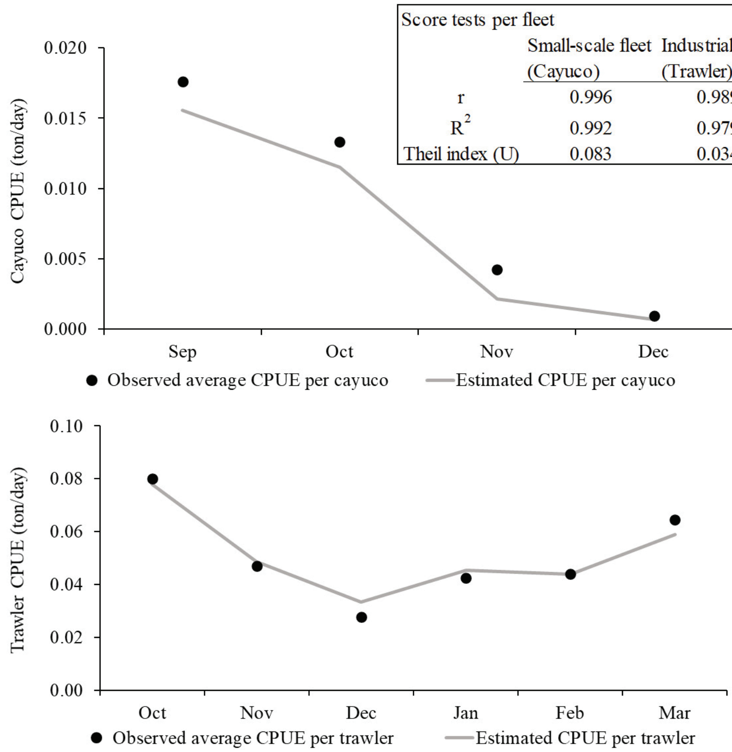


Figure 3 - Catchability-at-age values estimated per fleet, a) small scale fleet and b) industrial fleet, for the white shrimp fishery during the 2014-2015 season in southern Sinaloa.



Score tests per fleet	Small-scale fleet (Cayuco)	Industrial fleet (Trawler)
r	0.996	0.989
R^2	0.992	0.979
Theil index (U)	0.083	0.034

Figure 4 – Comparison between observed and estimated catch from the age-structured bioeconomic model for the white shrimp fishery, a) cayucos and b) trawlers, during the season 2014-2015 in southern Sinaloa.

The estimated parameters of the recruitment functions generated estimated CPUE values consistent according the observed CPUE (Table 2).

Status quo scenario

For the *status quo* scenario, the calculated biomass was 30,000 tons (Fig. 5), equivalent to 27% of the total virgin biomass and is below MSY (50%), indicating suboptimal or overexploited levels. The largest residual biomass accumulates at early ages and decreases considerably towards adulthood (Fig. 5). Likewise, a sharp decrease in biomass is observed towards the ages of first maturity or migration (ages 4-5) as a result of the simultaneous exploitation by both fleets.

The artisanal fleet showed higher landings of *L. vannamei* (~1,073 ton) than the industrial fleet (~460 ton) (Fig. 4 and Fig. 6). The most representative ages in the catch were age 4 for the small-scale fleet and age 5 for the industrial fleet (Fig. 6).

The estimated NPV resource rent for the 2014-2015 white shrimp fishing season were $5,334,219 USD for the small-scale fleet and $2,425,992 USD for the industrial fleet. The estimated NPV of resource rent (NPV) for a 5 years simulation period was $10,371,445 USD and $22,989,621 USD for the industrial and small-scale fleets, respectively (Table 5, Fig. 6). Resulting in an annual average NPV of $28,030 USD per trawler season^{-1} and $2,298 USD per cayuco season^{-1}.

Industrial fleet management scenarios

The fleet reduction management scenarios of the industrial effort on the shrimp fishery of southern Sinaloa causes a progressive differential improvement in the performance of all bioeconomic variables (Table 5; Fig. 7). The greatest benefit resulted from the NPV maximization strategy, with a reduction of 70% of the trawlers to overcome the constant small-scale fleet fishing mortality. Also, the fishery NPV increased 60% and the highest economic benefit was obtained per trawler (up to 908%). Similarly, biological indicators such as biomass, recruitment and spawning stock also showed an increase of 27%, 13% and 39% respectively. However, the final biomass was still below MSY ($0.34_{XmaxNPV}<0.5_{MSY}$). Also, the positive sequential externalities benefited the small-scale fleet by up to 4% in its NPV.

On the contrary, the entry of more trawlers (scenarios +25% and +50%) caused a decrease in all bioeconomic indicators and affecting mostly the industrial fleet, registering economic losses of up to -86% (Table 5; Fig. 7). The small-scale fleet presented negligible losses of -2%. The biomass, recruitment and spawning stock biomass decreased up to 12%, 8% and 16% respectively.

DISCUSSION

The bioeconomic age-structured model developed in this study, adequately represented the sequential white shrimp fishery of the 2014-15 season, as demonstrated by the *status quo* observed and estimated conditions. By reducing the effective industrial fleet, and maintaining the small-scale fleet constant, this study further showed that the fishery continued to be slightly overfished. Therefore, greater emphasis needs to be applied on managing the small-scale component to achieve the objective of maximizing the NPV of the fishery as a whole among other objectives. A decrease in the industrial effort caused positive externalities in the entire fishery, which relates to a higher conservation of the stock, an increase in industrial returns and marginally increases in the small-scale returns. This suggests a viable management strategy for sequential fisheries where the small-scale component is difficult or socially complex to regulate.

The key issues in the sequential white shrimp fishery in the Pacific (Sinaloa and Gulf of Tehuantepec) are the deteriorated status of its stocks due to an overcapitalization of both fishing fleets; illegal and furtive fishing; and the weak monitoring, surveillance, and enforcement (weak governance) of the small-scale fishing effort (Chávez-Herrera, 2001; Perez-Vivar, 2003; CONAPESCA, 2004; INAPESCA, 2012). The bioeconomic model shows for the analyzed 2014-2015 fishing season a *L. vannamei* stock decrease of 73% with respect to the calculated virgin biomass (X_{max}). This problem is recurrent and had already been reported for the species and area showing similar values in the population reduction of 76% (Pérez-Vivar, 2003) and 65% (Madrid-Vera *et al*., 2012), so historically it has not been possible to achieve an adequate fishing management. Moreover, this status of overexploitation was also observed in the white shrimp stock of the Gulf of Tehuantepec (Cervantes-Hernández *et al*., 2006; Cervantes-Hernández *et al*., 2008; Ramos-Cruz, 2013).

The effort estimated by the model was 2000 cayucos, equivalent to 2000 - 4000 fishermen (census reported by the Sinaloa fishing offices), but the effective fishing activity is reported to be at least 50% higher, consisting of subsistence or independent fishermen hired during the fishing season by the local cooperatives (source: interviews with 16 cooperatives in the area). According to the bioeconomic model, the overcapacity of the small-scale fishery presented high fishing mortalities over the specific juvenile ages (Fig. 6), decreasing the overall resource rent of the fishery due to the growth overfishing, presenting economic returns below of operating at MSY (*status quo* NPV ~$290 USD per artisanal fisherman month^{-1}). These income values were above the Mexican rural poverty line, considered as the minimum subsistence income for a person, and any income below it is considered poverty ($89 USD

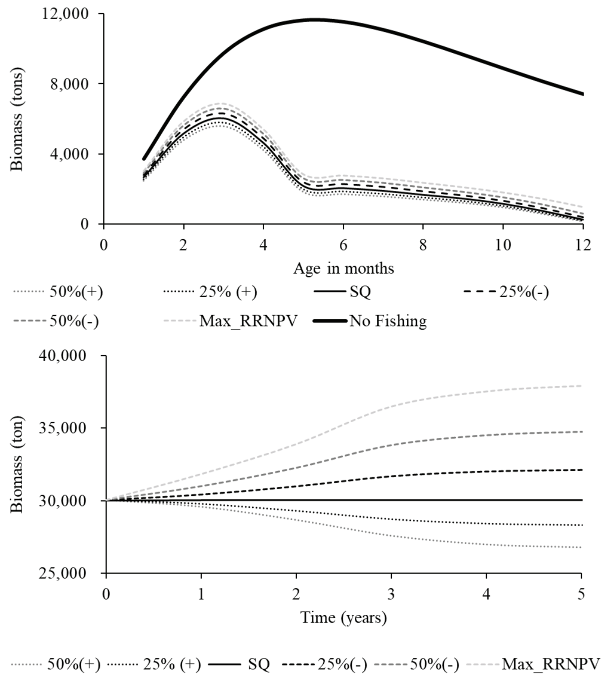


Figure 5 - Estimated biomass over time (above) and age-specific (below) for the sequential white shrimp fishery during the season 2014-2015 in southern Sinaloa. Scenarios: SQ, *status quo*; increasing industrial trawlers (+)20% and 50%; decreasing industrial trawlers 30%, 50%, ~70% (Maximization of the net present value of resource rent); No fishing: Removing all fishing mortality.

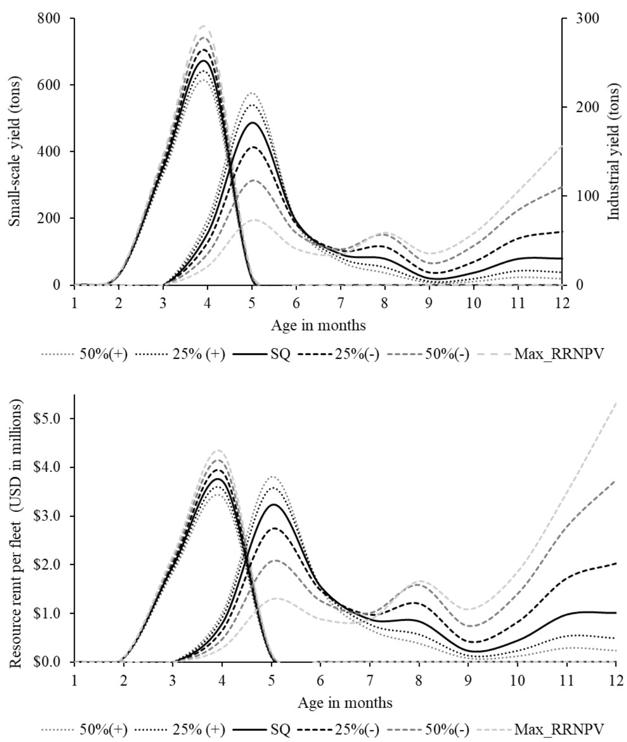


Figure 6 – Age-specific harvest (above) and revenues (below) per fleet for the sequential white shrimp fishery during the season 2014-2015 in southern Sinaloa. Scenarios: SQ, *status quo*; increasing industrial trawlers (+)20% and 50%; decreasing industrial trawlers 30%, 50%, ~70% (Maximization of the net present value of resource rent).

Table 5 – Bioeconomic outputs of management scenarios using industrial fleet vessels for the white shrimp fishery during the 2014-2015 season in southern Sinaloa.

	Industrial fleet management scenarios					
	50%	25%	SQ	-25%	-50%	-72%[2]
Cayucos	2000	2000	2000	2000	2000	2000
Trawlers	111	93	74	56	37	21
Fishery NPV[1] resource rent (USD)	-27%	-15%	$33,361,066	20%	44%	60%
Industrial NPV resource rent (USD)	-80%	-45%	$10,371,445	60%	134%	179%
Small-scale NPV resource rent (USD)	-3%	-2%	$22,989,621	2%	4%	6%
NPV resource rent per trawler (USD)	-86%	-56%	$140,155	113%	368%	908%
NPV resource rent per cayuco (USD)	-3%	-2%	$11,495	2%	4%	6%
Final biomass (ton)	-12%	-6%	30,057	7%	17%	27%
Total recruitment (individuals)	-8%	-4%	1.62E+10	4%	9%	13%
Spawning stock (ton)	-16%	-8%	16,153	10%	23%	39%

[1]NPV for a period of 5 years; [2]maximization of the NPV.

for 2014-2015; CONEVAL, 2018). When compared to the artisanal income of other Latin American countries, it was slightly higher than the reported for Colombia ($200 USD fisherman month^{-1}), similar to Peru ($300 USD fisherman month^{-1}) and lower than Chile ($728 USD fisherman month^{-1}) (García *et al*., 2019). On the other hand, the industrial fleet presented an average resource rent (average NPV ~$28,000 USD per trawler season^{-1}) compared to other trawlers operating in other regions of Mexican Pacific [i.e. average NPV per trawler season^{-1} for the Gulf of California was ~$21,000 USD to $35,000 USD (Almendarez *et al*., 2015; staff communication SADER, 2020)].

Several authors have argued that in the absence

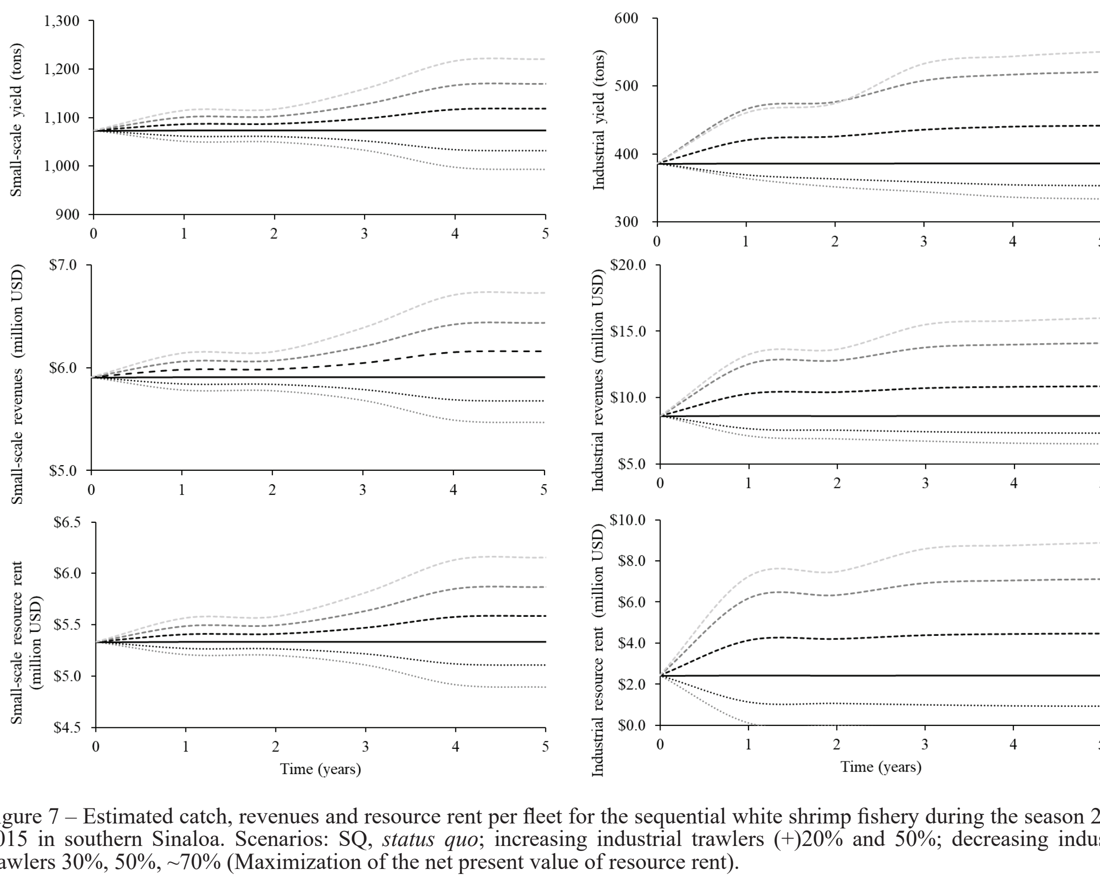


Figure 7 – Estimated catch, revenues and resource rent per fleet for the sequential white shrimp fishery during the season 2014-2015 in southern Sinaloa. Scenarios: SQ, *status quo*; increasing industrial trawlers (+)20% and 50%; decreasing industrial trawlers 30%, 50%, ~70% (Maximization of the net present value of resource rent).

of effective measures to limit access, no manage-ment strategy will produce the expected improve-ments in the yield of the fishery (Ward *et al*., 2004;Anderson & Seijo, 2010). Managing industrial effort while keeping artisanal effort constant allowed for a decrease in industrial total fishing mortality over the spawning stock component which resulted in a 27% biomass increase over thestatus quo, but still below MSY($0.34_{MaxNPV}<0.5_{MSY}$); although García & Le Reste (1986) suggested that values of 0.32 – 0.44 for final virgin biomass were appropriate for tropical penaeids. The proposed industrial management strategies are intended to conserve adults while maintaining high fishing mortality in juveniles (caused by the un-controlled artisanal fleet), varying in the observed bioeconomic performance depending on the level of industrial effort removed. This follows the hypothesis that the probability of death in juveniles is higher than in adults, under the assumption of differential natural mortality-at-age, reaffirming that the best strategy in unregulated sequential fisheries is to protect the reproductive component over juve-niles (Caddy & Seijo 2002; Caddy, 2018).

As observed in this study, even with the bio-mass in a sub-optimal state, the average resource rent per ship increased to ~$282,654 USD (+908%)at the expense of ~70% of the industrial fleet for the area (for the NPV maximization scenario). This laissez-faire approach (i.e. recognizing difficult rea-lities, yet giving no priority to the management of the small scale fishery: Guillet, 2011), where sma-ll-scale shrimp fisheries are almost impossible to manage and attention is paid to industrial fisheries,deserves more attention for Mexico, where there are mechanisms to control the industrial fleet by purchasing the trawlers (direct effort reduction) or restricting them to certain areas (VMS monitoring)(INAPESCA, 2016). The distribution of the benefits of the proposed management strategies on the indus-trial fleet allowed maintaining the observed artisanal effort (i.e. providing a source of income and food for approximately 2000 artisanal fishermen), with final biomass levels close to MSY, and also creates a con-siderable economic benefit in the industrial fishery (see Table 5 NPV resource rent per trawler) at the trade-off of reducing by 25% or more (*i.e.* 18 vessels 108 jobs: Almendárez-Hernández *et al*., 2015) the observed effort in the area. However, due to the high income derived from this reduction, these lost jobs may be incorporated into some link of the industrial shrimp fishery value chain.

The Australian Boreal shrimp fishery is a global example of an effective fisheries management (Gui-llet, 2011; Pascoe *et al*., 2016), where 40% of the trawling fleet was reduced (i.e. 25% in 2002/03 and another 15% in 2006/07) to maximize its economic performance. Unlike Mexico, their Boreal shrimp fishery do not have an artisanal fleet, and since Mexican policies are focused on social protection, the rent maximization is not a management measure that is socially accepted as public policy (Nance *et al*., 2008). Therefore, the present bioeconomic model worked under the condition of Pareto security for the small-scale fishery, where no economic damage was allowed to any user, only their welfare could be increased, or they could remain instatus quocondition.

The present study establishes an age-structured bioeconomic model for the sequential fishery of white shrimp (*L. vannamei*). Even though the proposed progressive reduction of the industrial fleet has generated positive bioeconomic externalities to the fishery, it is necessary to explore more management strategies that include the small-scale fishery, taking the sequential fishery to sustainable levels and higher profitability for users. The inherent charac-teristics of the resource such as its short cycle and high fecundity have also mitigated the effect of high levels of fishing exploitation on the resource over time.

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