Sustainable management of a new fishing stock: bioeconomic approach under biological and market uncertainty

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Abstract: Potential and emerging fisheries create challenges and opportunities for fishery managers who need to decide how to sustainably manage a fishery that does not yet exist. A new Pacific hake stock off the west coast of Mexico has been identified. The Mexican government is interested in assessing the feasibility of a new commercial fishery. This work proposes and analyzes alternative potential fishery management measures for this possible new fishery under biological and market uncertainties. Results indicate that a new fishery could be biologically sustainable and economically profitable under a set of management strategies and control rules. A limited access strategy with low effort is recommended because it is most profitable per vessel and biologically cautious, considering the high uncertainty associated with the exploitation of an unfished stock. Despite the combination of high operating costs and low prices the fishery could still be profitable in the long-term, although there is risk of overexploitation if high fishing effort is allowed. Nevertheless, our results suggest low risk of fishing down the dwarf hake stock if the fishery is managed under low effort levels, allowing for sufficient opportunities for data collection and adaptive management. This work addresses the rare opportunity of assessing a fishery previous to its operation, with all the associated data limitations and uncertainty.

Key words: unfished stock, bioeconomic analysis, Monte Carlo risk analysis, Pacific dwarf hake.

1 Introduction

A potential new fishery poses new opportunities and challenges, as potential new revenues and jobs must be balanced with the inherent biological and market uncertainty surrounding an unexploited resource. Management bodies need to determine the objectives for the new fishery and asses which management measures would best meet them. These decisions are often based on potential economic profitability and biological sustainability, which can be assessed by bioeconomic models under alternative management measures and given the inherent uncertainty. The Pacific hake *Merluccius productus* (Ayres, 1855) is a target species of important fisheries throughout its range, from the coasts of Alaska to the South of Mexico (Lloris et al., 2005). While in the US and Canada, Pacific hake is one of the most abundant species of commercial importance, reaching yields over 400,000 metric tons (Grandin et al., 2020), fisheries in Mexico are just beginning to emerge. In Mexican waters, *M. productus* along the Pacific coast of the Baja California peninsula exhibits morphological differences (having notably smaller size), and is known as dwarf hake (Vrooman and Paloma, 1977; Balart, 1996; Zamora-García et al., 2020). Although an emerging hake fishery exists on the east coast of Baja California (Upper Gulf of California, UGC), regulated in 2018 by granting 80 permits (Zamora-García et al., 2020), dwarf hake on the west coast of Baja California is not currently exploited. The abundance of local stocks in this latter region have been estimated on different occasions (Balart, 1996). Beginning in the 1980s, Padilla-García and de la Campa de Guzmán (1981) estimated between 395 and 583 thousand tons of biomass off the western coast of Baja California Peninsula by larval and egg abundance. Later, Schmitter-Soto et al., (1992) estimated on the continental shelf of the west coast of Baja California Sur (BCS), a biomass ranging from 151 to 230 thousand tons by the swept area method (Baranov, 1918). More recently, Godínez-Pérez (2013) estimated a biomass of 146,000 tons using hydroacoustic and 150,000 tons by the swept area method, giving a reasonable certainty level about current biomass levels in the surveyed area known as Gulf of Ulloa.

Following these prospective results, dwarf hake off the west coast of BCS is seen as an unexploited resource with important fishing potential (Balart-Páez, 2005; Balart, 1996; Salinas-Mayoral, 2018). Therefore, the Mexican government is exploring the possibility of opening a new fishery in the region, which may bring a source of income, jobs, and alternative or complementary activity for participants in already overcapitalized existing fisheries in the region (Almendarez Hernández, 2013).

The opening of a new fishery targeting dwarf hake on the western coast of BCS requires the assessment of possible exploitation scenarios and corresponding biologic and economic performance. Therefore, the objective of this work is to analyze possible bioeconomic impacts of alternative management strategies on the newly surveyed stock, considering the high uncertainty associated with establishing a new sustainable fishery.

2 Material and methods

2.1 Study area

The present work analyzes the dwarf hake off the western coast of BCS, in the region of the Gulf of Ulloa (GoU), located south of Punta Eugenia and north of Magdalena Bay, between 24° and 26° 30 'N (Cordero-Tapia and Reséndiz-Morales, 2014) (Figure 1). This area is situated in an important oceanic upwelling zone in the southernmost region of the California Current and has been defined as a Biological Action Centre (BAC, Lluch-Belda et al., 2000). The reason for studying this area is that there is up-to-date information on the biomass and distribution of hake in the GoU (Godínez-Pérez, 2013), as well as information on prospective yields and costs from a research study carried out by a joint project by national and local research institutions (CIBNOR-CONACyT[*]) from 2011 to 2018 in the same area.

[Figure 1]

Our analysis assumed the dwarf hake stock is an independent stock, following Funes-Rodríguez et al., (2009) that suggests the existence of physical barriers off the mid Baja California Peninsula (Punta Eugenia region) that possibly restrict gene flow between northern populations and dwarf hake. Additionally, Salinas-Mayoral (2018) concluded that life history traits of dwarf hake are substantially different from those in northern latitudes, suggesting they are different stocks.

2.2 Age structured model

The population dynamics of the dwarf hake stock is represented with an age-structured bioeconomic model, following Anderson and Seijo (2010). Fifty-year projections were performed, beginning with unfished biomass to represent the situation of a new unexploited stock.

2.2.1 Biologic sub-model

2.2.1.1 Individual growth

The estimation of the mean length at age was based on the von Bertalanffy growth model, which has been shown to adequately represent the growth of dwarf hake (Mora-Zamacona et al., submitted):

$$L_t = L_\infty\left[1 - e^{-k(t-t_0)}\right] \tag{1}$$

where L_t is the average standard length at age t, L_∞ is the maximum average length, k is the individual growth rate, t_0 is the theoretical age at zero length (Pauly, 1981). The values of the parameters used were: L_∞ = 28.23 cm, k = 0.251, t_0 = 0.01 (Mora-Zamacona et al., submitted).

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2.2.1.2 Length-weight relationship

To estimate the average weight at age (w_i), the parameters of the length-weight relationship (standard length and total weight) reported by Salinas-Mayoral (2018) for the stock of dwarf hake of the western coast of the Baja California Peninsula were used (a = 0.009, b = 2.98):

$$w_i = aL^b \tag{2}$$

2.2.1.3 Recruitment

Due to the scarce information regarding the recruitment of the dwarf hake (influence of the environment, food availability, presence of predators, etc.), the existence of a relationship between the number of organisms recruited to the population and the spawning stock biomass was assumed to follow the Beverton-Holt relationship (Beverton and Holt, 1957), since it has been shown to adequately represent the recruitment of the species in other areas (Grandin et al., 2020). The equation used follows the parameterization of Methot and Taylor (2011), which in turn integrates the modification proposed by Mace and Doonan (1988):

$$R_y = \frac{4hR_0S_y}{S_0(1-h)+S_y(5h-1)} \tag{3}$$

where *h* is the steepness parameter of the stock-recruitment function and is related to the productivity of the stock at low stock size (Grandin et al., 2020), defined as the fraction of unfished recruitment that is obtained from a spawning biomass equivalent to 20% of the unfished spawning biomass (Hilborn and Walters, 1992; Mace and Doonan, 1988). S_0 is the unfished spawning biomass that corresponds to an unfished recruitment R_0; and S_y is the spawning biomass in year *y* resulting in recruitment R_y.

The age of recruitment was considered as age class one because it is the first year class susceptible to fishing gear for dwarf hake (Salinas-Mayoral, 2018). The unfished spawning biomass S_0 was estimated considering an age of first maturity of 2 years and a sexual proportion of 0.5 (Salinas-Mayoral, 2018). Likewise, the corresponding unfished recruitment R_0 was estimated as the number of recruits necessary in the population to maintain the unfished stock biomass (Godínez-Pérez, 2013). The stock-recruitment steepness parameter was assumed to range between 0.5 and 0.8, mimicking the productivity of the hake stock in the US and Canada (Grandin et al., 2020).

2.2.1.4 Natural mortality

In the present work, it was assumed that there is a decrease in natural mortality (*M*) with age following Chen and Watanabe (1989), who related *M* with age through the von Bertalanffy growth parameters. The equation used assumes that there is no senescent period for hake:

$$M_i = \frac{k}{(1 - e^{-k(i-i_0})} \qquad (4)$$

where *i* is the age in years; *k* and t_0 are parameters of the von Bertalanffy growth model. Maximum age was considered to be 10 years and dwarf hake growth parameters were taken from Mora-Zamacona et al., (submitted). Resulting natural mortality rates at age are shown in Figure 2.

[Figure 2]

2.2.1.5 Population dynamics

The dynamics of the population were represented using the following equation:

$$N_{i+1,t+1} = N_{i,t}e^{\left(-\left(F_{i,t}+M_i\right)\right)} \qquad (5)$$

where $N_{i+1,\,t+1}$ is the number of individuals in age class $i+1$ at time $t+1$, $F_{i,t}$ is the fishing mortality at age *i* and time *t*, and M_i is the natural mortality at age *i*. Catches were estimated by age class ($Y_{i,t}$) as follows (Quinn and Deriso, 1999):

$$y_{i,t} = N_{i,t} w_i \left(\frac{F_{i,t}}{F_{i,t} + M_i} \right) \left(1 - e^{(-(F_{i,t}+M_i))} \right) \quad (6)$$

and the fishing mortality rate was estimated as:

$$F_{i,t} = q_i f_t \quad (7)$$

where q_i is the catchability at age i and f_t is the effort at time t. Catchability was assumed to increase 2% annually over the 50 year projection to account for improvements in fish-finding behavior and technological creep of the fishery, which may cause the effective capacity of a fleet to increase over time (Cochrane and Garcia, 2009; Palomares and Pauly, 2019). Catchability was estimated with the Baranov equation (Baranov, 1918):

$$q_i = -\left\{ ln \left[1 - \left(c \frac{a}{Area} \right) SEL_i \right] \right\} \quad (8)$$

where c is the probability of catch, a is the area swept per vessel per year, *Area* is the area of distribution of the resource and SEL_i is the selectivity of the fishing gear by age class i. The area swept per vessel per year was estimated from the survey carried out in the GoU in 2011 as a= 8.89 km^2/vessel/year, while the area of distribution of the resource was estimated to be *Area*= 9,210 km^2, by Godínez-Pérez (2013).

Selectivity of the fishing gear by age class is given by:

$$SEL_i = \frac{1}{1 + e^{(s_1 - s_2 L)}} \quad (9)$$

where:

$$s_1 = L_{50\%} \left(\frac{ln3}{L_{75\%} - L_{50\%}} \right) \quad (10)$$

$$s_2 = \frac{s_1}{L_{50\%}} \quad (11)$$

where $L_{50\%}$ and $L_{75\%}$ are the length of the organisms with 50% and 75% of retention by the fishing gear, respectively. These parameters were estimated from the size structure reported in the prospective catches (CIBNOR-CONACyT, 2011) by maximizing the negative log-likelihood value with a nonlinear fit using the generalized reduced gradient method, assuming a multiplicative error in the residuals (Wang and Liu, 2006) and using the value reported by Mathews (1975) ($L_{50\%}$= 11.25 cm) for the dwarf hake in the southern Gulf of California as a seed value.

2.2.2 Economic sub-model

In the present work, for simplicity and due to the lack of available data to support more complex assumptions, a homogeneous behaviour of fishers and fleet characteristics was assumed. Exploring the possible implications of heterogeneity dynamics among the fishing fleet under alternative management strategies may be beneficial in future work, as each fisher likely has its own preferences that varies the value they place on their money, time, skills and cultural importance, which fosters heterogeneity in fisher behaviour (Salas and Gaertner, 2004). The dynamics of the fishing fleet were represented using the function described by Smith, (1969) which assumes that the changes in fishing effort f (number of vessels operating within a fishing season), are proportional to profits (π):

$$f_{t+1} = f_t + \varphi\pi_t \tag{12}$$

where φ is the positive constant of fleet dynamics; and π are the profits obtained in time t. Taking as a reference the industrial fleet of the bottom trawler *M. hubbsi* and *M. australis* fishery, Portela et al., (2002) reported a historical annual change in effort around 2-8 major vessels. Therefore, the φ value used in this research was calculated in order to reflect a similar vessel dynamic (entry/exit) to the mentioned fleet targeting other *Merluccius* species, finally reaching the value of φ= 3.50E-06

In this study, it was assumed that fishing vessels targeting the new hake stock in the GoU will be based in the Bahia Magdalena port, moving annually from Mazatlan port (Sinaloa state, see

Figure 1). The latter is the current origin port of the potential finfish and shrimp fishing vessels that may redirect operations to this potential dwarf hake new fishery each year at the end of shrimp season (returning to the original port for the next shrimp/finfish season). This yearly displacement of fishing effort from the Gulf of California to the west coast of BCS is included into the fishing total costs. It is assumed that fishing season goes from March to May (after shrimp season), and each vessel performs a fixed effort of five trips per season and 5 days per trip. This assumption is based on fishing effort trends observed in the east coast of Baja California Peninsula (Upper Gulf of California) where Pacific hake is currently exploited.

The variable, fixed and opportunity costs are shown in Table 1. The USD exchange rate used was 1 USD= 20 MXN. The opportunity cost of labor was calculated as the possible profits generated by the crew with a minimum federal wage during the fishing season (three months).

[Table 1]

The profits were calculated as the subtraction of total costs from total revenues as follows (Seijo et al., 1997)

$$\pi_t = TR_t - TC_t \tag{13}$$

$$TR_t = pY_t \tag{14}$$

$$TC_t = VC_t + FC_t + OC_t \tag{15}$$

where: π_t are the profits; TR_t are the total revenues; TC_t are the total costs; p is the price, which was assumed constant by size and over time; VC_t are the variable costs, calculated with the effort above mentioned; FC_t are the fixed costs; OC_t are the opportunity costs. All vessels in the dwarf hake fishery are expected to be currently participating also in the shrimp fishery and the fixed costs are assumed to be covered by the latter. Information on operating costs of the fleet were obtained from reports of the prospecting cruises carried out by CIBNOR, which departed from Magdalena Bay to the fishing zone in the GoU.

For the price of sale *p*, values between 0.75 and 1.0 US/kg were used, based on interviews of producers of hake in the UGC. The fishery value was calculated by net present value (NPV) of the profits achieved through the analyzed time, following:

$$NPV = \sum_{i=0}^{n} \frac{\pi_t}{(1+d)^t} \tag{16}$$

where *n* refers to the projection vector, *d* is the annual discount rate and *t* is the projection time in years. In this case, *d* was estimated as the subtraction of annual inflation (3.7%) from the returns obtained from the CETES (Mexican Federal Treasury Certificates; 6.81%), leaving *d*= 3.11% (values estimated in February-2020). The NPV was calculated for a time horizon of 50 years. The summary of the parameters used in the age-structured bioeconomic model is shown in Table 2.

[Table 2]

2.2.3 Model validation

To validate the model, information from the prospective study carried out in a joint project by national and local research institutions (CIBNOR-CONACyT) in 2011 was used. Data included hake-specific CPUE estimates of fishing days in the GoU region by a trawler fishing vessel. The discrepancy between the observed prospective CPUE and the model estimated CPUE was assessed using the Theil statistic, which is a non-parametric estimator with values between (0,1) and a critical value of U= 0.2. Further, the bias proportion (U_B), variance proportion (U_V) and covariance proportion (U_C) were calculated (Araneda et al., 2013; Duarte et al., 2018; Power, 1993).

2.3 Evaluation of management strategies

The effects of five alternative management strategies were evaluated. Two strategies based on effort control by limiting access, two strategies that combine effort control and catch limit, and an open access scenario. All strategies considered an initial effort of 20 vessels in time t= 0:

f_{20}: effort limited to a maximum of 20 vessels, based on the number of UGC hake fishery permit holders currently not harvesting the species.

f_{80}: effort limited to a maximum of 80 vessels, equal to the number of permits granted in the Mexican hake fishery currently operating in the UGC.

TAC_{TRPf80}: a total allowable catch with limited effort to 80 vessels, intended to maintain a biomass target reference point (TRP) of 100,000 t (TAC_{TRPf80} = 7,000 t), which ensures precautionary stock biomass levels in the long-term.

$TAC_{LRPf120}$: a total allowable catch with limited effort to 120 vessels intended to maintain a biomass limit reference point (LRP) of 75,000 t (half the described unfished biomass) while maximizing yields ($TAC_{LRPf120}$= 9,500 t).

OA: an open access scenario representing an unmanaged "control scenario" fishery,

The biomass reference points were selected considering that a LRP of half the unfished biomass approximates the maximum sustainable yield and a TRP of 100,000 t is a precautionary biomass level equal to two thirds of the unfished biomass. In reference to the combined catch-effort control strategies (TAC_{TRPf80} and $TAC_{LRPf120}$), the catch quotas were estimated based on the parameters' median values (Table 2), although we acknowledge the influence of parameters uncertainty in each TAC value. Finally, we assumed an individual quota restriction rule to avoid race-for-fish behaviour in both TAC_{TRPf80} and $TAC_{LRPf120}$.

2.3.1 Risk and uncertainty

To assess the sensitivity of the response variables of interest (biomass and NPV of the fishery) to the model parameters, a sensitivity analysis was previously carried out varying the model parameter values in ±10% with a uniform probability distribution, under the management strategies above mentioned. The parameters that influenced the results differed between strategies, but the ones that showed the greatest influence for all strategies were the growth parameters L_∞ and k, the price of sale p, steepness h, unfished-stock recruitment R_0 and the fishery dynamics constant φ. Therefore, variability in these parameters was explored to evaluate risk and uncertainty in the potential dwarf hake fishery.

2.3.1.1 Monte Carlo Analysis

A Monte Carlo analysis was performed to estimate the probability (risk) of population biomass declining below the TRP and LRP biomass levels under the different management strategies proposed, after 50 years of fishing activity. Uncertainty was considered for the most sensitive parameters, with a uniform probability distribution between the value ranges described in Table 3.

[Table 3]

Additionally, the interquartile range and median values were estimated for the proportion of unfished biomass over time (B_t/B_0), the profits per vessel (π_t/vessel), and the number of vessels employed at the end of the simulation period. The analysis was performed with a risk analysis tool (Crystal Ball ©), simulation period was 50 years, and the number of permutations per simulation was 10,000.

3 Results

3.1 Model validation

The Theil inequality coefficient showed that the model accurately reproduced the prospective CPUEs as the Theil's U value was less than 0.2 (Table 4). The bias proportion (U_B) and the variance proportion (U_V) are the partial inequality coefficients with higher proportions, which can be further reduced by increasing the size of the data set available once the fishery operates.

[Table 4]

3.2 Fishery dynamics

The dynamics of the fishery considering the median values of the model parameters (Table 2) showed that biomass of the stock may be reduced below the LRP (half the unfished biomass) when operating under open access (Figure 3). Under these conditions the combined catch-effort control strategies succeeded in maintaining biomass levels above their respective fishery reference points, while the limited access strategies showed a continuous decrease in biomass driven by the creep factor, nonetheless, the f_{20} strategy achieved the highest biomass level.

[Figure 3]

The dwarf hake fishery annual yields oscillated between 2 and 12 thousand tons, with the highest values for the *OA* and the lowest for the f_{20} strategy. The TAC_{TRPf80} and $TAC_{LRPf120}$ strategies reached their catch quotas around years 15 to 18 and maintained that level thereafter, while the limited access strategies showed a persistent increase in yields (creep factor), coinciding with a continuous increase in the fishery profits.

The fishery's overall profits were highest for the f_{80} strategy, followed by f_{20}, while *OA* obtained the lowest, as it achieved bioeconomic equilibrium. The f_{80}, TAC_{TRPf80} and $TAC_{LRPf120}$ strategies showed a drop in the fishery profits around years 12 to 18, corresponding to the periods where maximum effort level was reached and catch quota was met, respectively. Interestingly, f_{80} and TAC_{TRPf80} reached the 80 vessels effort level at the same time (year 15) but the drop in profits occurred earlier for TAC_{TRPf80}, when the yields approached the catch quota (year 13), while f_{80} showed an increase in yields for a couple years longer. The effort of every strategy achieved their maximum restricted levels and maintained them thereafter, except for *OA* that showed a decrease after taking losses in year 30 and oscillated around 160 vessels after reaching bioeconomic equilibrium.

3.3 Monte Carlo Analysis

The most conservative strategy was the f_{20} strategy, which was the only one with no risk of falling below both the TRP and LRP, maintaining the highest biomass level from the assessed management strategies (over $0.8B_0$) (Fig. 4). The f_{80} strategy showed high risk of falling below the TRP (94%) and low risk of decreasing biomass below LRP (6%), keeping a biomass level around $0.57B_0$. The combined catch-effort control strategies were successful in maintaining biomass around their target levels TAC_{TRPf80} (B_{50}<TRP= 27%, ~$0.72B_0$) and $TAC_{LRPf120}$ (B_{50}<LRP= 33%, ~$0.55B_0$) (Table 5). For the open access scenario, there was 100% risk of falling below both reference points.

[Figure 4]

The profits per vessel showed high variability in f_{20} and f_{80}, nonetheless, these strategies had the highest and second highest values (~$127,000 and ~$47,000 USD, respectively) (Fig. 4). The TAC_{TRPf80} and $TAC_{LRPf120}$ strategies led to lower profits per vessel, particularly the latter, which had profits around $6,000 USD. The value of open access profits per vessel ranged around zero, indicating a bioeconomic equilibrium situation.

The NPV of the fishery under the f_{80} strategy showed the highest values but also the highest variability, followed by f_{20} and the combined catch-effort control strategies. For the fishing effort (number of vessels), the only strategies that led to different values were $TAC_{LRPf120}$ and open access.

[Table 5]

4 Discussion

The potential dwarf hake new fishery assessed here opens the opportunity for fishermen targeting other species to diversify their fishing, while using a capital that would be otherwise idling. We assessed the scenario of shrimp fishermen from Mazatlan entering the new dwarf hake fishery, as they already have the capital costs covered. In this sense, our results indicate that a fishery for dwarf hake may be a biologically sustainable and economically profitable activity, even considering the high costs of vessel displacement from the Gulf of California to the west coast of BCS.

It is important to mention that in our study we opted for a model that assumes a homogeneous behavior of the effort, such as the Smith's model, which does not account for the behavior of the harvesters, except for the entry and exit of vessels. However, the model was considered to be adequate because all potential entrant vessels have similar characteristics (shrimp trawlers of Sinaloa state, (Almendarez Hernández, 2013) and, additionally, it was assumed that the possible changes in effort due to changes in fishing days or number of trips, are not large relative to a new entry of a vessel.

Potential participants of this new fishery may consider their opportunity costs, which may be higher as they have alternative economic activities, both in the fishing and non-fishing sectors (Yew and Heaps, 1996). In our case study, for the capital costs, the shrimp fleet is currently inactive outside the shrimp fishing season (Salinas-Zavala, pers. comm.), which implies having productive assets idling part of the year with the associated capital losses. On the other hand, fishers may work in non-fishing activities out of the shrimp season, which was accounted for with the opportunity costs of labor, although in a general way, fishermen are characterized by a high attachment to their activity (Pollnac and Poggie, 2008). In this sense, having the new dwarf hake fishery alternative would allow them to diversify their fishing, which may be preferred over turning to a different activity.

Fisheries focusing on abundant high-value species may be more economically viable, but also tend to be vulnerable to external drivers (environment, market variation, etc.) (Anderson et al., 2017; Giron-Nava et al., 2018). In particular, the Mexican Pacific shrimp fisheries have shown high variability in yields (Almendarez Hernández, 2013), and events like the 2015 shrimp fishery ban in the UGC (DOF, 2015) and the recent US ban on Mexican shrimp imports, have affected the fishermen (CONAPESCA, 2021). Diversifying the target species has been proposed as a possible risk-reducing strategy (Anderson et al., 2017; Kasperski and Holland, 2013; Smith and McKelvey, 1986), in this sense, fishing dwarf hake may be a complementary or alternative economic activity and may increase the fishing fleet's resilience through time (Finkbeiner, 2015). As a fishery begins its operations it is important to assign permits to limit the access and prevent an excessive increase of production that may lead to the resource rent dissipation (overcapitalization) or affect the stock (overexploitation) (Gordon, 1954; Homans and Wilen, 2000). In our study, the twenty-vessel limited-access f_{20} strategy proved to be the most profitable per vessel and a cautious measure, as it maintained the highest biomass levels among the assessed management strategies. Noteworthy, this conclusion is conditional on the 50-year time horizon, as the increase in efficiency of the fleet produced by the creep factor may result in a decrease in biomass that could continue, for which eventually an output control or harvest control rules may be required to ensure high biomass levels.

Regarding the limited -access strategies, it has been traditionally discussed that they may drive a fishery to overexploitation and little or no economic profit (Anderson et al., 2018), because even with a regulated nominal effort the effective effort may increase (Palomares and Pauly, 2019), particularly in the long-term. This was observed in the results with the dynamic trajectories, as yield/profits continuously increased and stock biomass decreased, which was more evident for the f_{80} strategy. The importance of accounting for the creep factor may be of special interest in the dwarf hake new fishery because the efficiency of the fleet may increase quickly during its early operations as the fishermen will first learn to catch a new resource.

The f_{80} strategy led to a profitable fishery with high yields during the 50-year time-horizon, but also produced a considerable impact to the stock, suggesting that if no other regulation is implemented overexploitation may occur in the long-term (Anderson et al., 2018). Interestingly, despite the biomass impact, f_{80} strategy presented the highest NPV, this is because the strategy did not consider an output control, hence allowed for high yields in the initial years of the fishery when fish stock was at its carrying capacity. These yields may be unsustainable in the long-term, compared to a more conservative approach (TAC_{TRPf80}). In this sense, it is useful for maintaining a desired biomass level to implement an output control in addition to the control of yields (Cochrane and Garcia, 2009) also dealing in this way with the capital stuffing that may increase the effective effort inadvertently. Moreover, it is possible that a race-to-fish behavior occurs in situations where there is a "common-pool" of the resource (Rust et al., 2016), therefore, to avoid such behavior, a management scheme such as individual catch quotas was considered in the TAC_{TRPf80} and $TAC_{LRPf120}$ strategies.

Our results showed that both combined catch-effort control strategies succeeded in maintaining the stock biomass around their objective reference point level, although the profits per vessel were reduced. For the TAC_{TRPf80} strategy a change in the number of vessels over time was not observed, implying that the fishery was profitable considering the uncertainty and the catch restriction for an 80-vessel fleet. In contrast, $TAC_{LRPf120}$ showed a low risk of taking losses and subsequently reducing the number of vessels, indicating that the catch restriction placed to maintain biomass above the LRP was not always profitable for a 120-vessel fleet, considering the uncertainty.

A common target reference point intended to achieve sustainable use of marine resources is MSY (Martell and Froese, 2012; UNCLOS, 1982), even though it is an exclusively biological reference point and other fishery objectives, such as social and economic, may require alternative management strategies (Giron-Nava et al., 2018). In fact, many fisheries worldwide have MSY as a target reference point, including hake fisheries such as *M. gayi* in Chile (SUBPESCA, 2016a), *M. australis* in Chile (SUBPESCA, 2016b) and *M. merluccius* in the Cantabrian Sea and Atlantic Iberian waters (ICES, 2020). In our study, the LRP of half the unfished estimated biomass ($0.5B_0$= 75,000 t), used as an approximation to the MSY biomass, proved to be profitable in the long term, although high effort led to risk of taking losses ($TAC_{LRPf120}$). Meanwhile, in the *OA* scenario biomass decreased even below LRP and fishing vessels increased over 120, putting the stock at risk of overexploitation. Considering the uncertainty of the new fishery, it is recommended to manage it using a higher biomass level TRP such as the one we explored, in addition to keeping a limited access to a reduced number of vessels that increases the rent of the resource.

Our study considered uncertainty in biological and economic parameters to account for the factors that may produce changes, both in the population dynamics and in the fishing fleet, which in turn affect the fishery's impact on the stock. Factors such as the increasing environmental variability in a changing climate (Easterling et al., 2000) may produce alterations to the dynamics of the stock, like reduced recruitment and survival (Smith and McKelvey, 1986); technological creep and fish-encountering improvements may increase the catchability of the fleet (Eigaard et al., 2014); and market-induced variability, such as supply and demand shifts, may influence the price of sale (Fryxell et al., 2017). In this sense, to reduce risk of overexploitation, regular assessments and surveys are needed, as well as an active management to adjust any input or output control to the changing conditions.

Special attention must be placed on the recruitment variability. For the US-Canada *M. productus* coastal stock the recruitment success affects the profitability of the fishery, as the fleet depends on infrequent large year-classes to sustain the fishery for years at a time (Grandin et al., 2020). The success in recruitment has been hypothesized to be related to the environmental conditions (Bailey and Francis, 1985; Hamel et al., 2015; Ressler et al., 2007), although its exact drivers are still uncertain. In our study we integrated recruitment and steepness uncertainty, which may be related to environmental variations, nonetheless, it is recommended to further analyze the influence of environment in the productivity of the dwarf hake stock.

When evaluating the benefit society can obtain from the new dwarf hake fishery the f_{80} strategy showed the highest NPV, although the discount rate may vary over time as social preferences change, which would modify our results. Furthermore, taking NPV into account as the only decision criterion is risky, due to the high contribution of early net benefits especially with a high discount rate, that could lead to the stock depletion in the first years of exploitation (Knoke et al., 2020). This outcome may affect the resource users that depend on continuous income from the fishery.

For the social objectives of the new fishery, the generation of jobs would be an imminent result, but the number of jobs produced should not be considered as the only or main indicator of social benefit, because this could be erroneously obtained with open access, as shown in our analysis, where *OA* provided the highest number of vessels (around 168 vessels). Instead, social objectives in fisheries have been recommended to move beyond merely focusing on employment (Hilborn, 2007) and consider remuneration to crew members (Maynou, 2021), which in this study is best covered with a limited access and small fleet f_{20} strategy, as higher profits per vessel were obtained.

This study addresses the rare opportunity of assessing a fishery previous to its operation. The importance of studying a “currently unexploited stock” is to assess the feasibility of different management scenarios without the risk of actually overcapitalizing the fishery or overexploiting the stock, which is the ideal way to start a fishery. Not only we are dealing with uncertainty and data limitations, similar to data-limited fisheries, but also, we are dealing with the lack of actual data on fishing yields and effort.

The results of this research suggest the GoU hake stock could support a new fishery as a possible alternative for vessels currently targeting other species. Although the dwarf hake fishery presents a high-cost low-price dynamic, our results showed risk of overexploitation when high fishing effort occurs, and the resource is not appropriately managed. Depending on the management objectives the new fishery could be managed in different ways. However, owing to the high uncertainty in the stock and market variability, a precautionary approach would have lower risks. Furthermore, our study suggests that the dwarf hake stock will not likely be fished down in a short period of time if the fishery is relatively small, thus, providing an opportunity for data collection during the fishery early operations that could substantially reduce uncertainty in some of the biological parameters, and allowing management to be updated.

CRediT authorship contribution statement

Pablo Mora-Zamacona: Conceptualization; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing. **César A. Salinas-Zavala:** Conceptualization; Investigation; Funding acquisition; Investigation; Project administration; Resources; Writing - review & editing. **Raúl R. Villanueva-Poot:** Conceptualization; Investigation; Methodology; Software; Visualization; Writing - review & editing. **Enrique Morales-Bojórquez:** Investigation; Supervision; Writing - review & editing. **Fernando I. González Laxe:** Investigation; Supervision; Writing - review & editing. **Kristin N. Marshall:** Investigation; Supervision; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

P. Mora-Zamacona gratefully acknowledge doctoral grant from the Consejo Nacional de Ciencia y Tecnología (contract number 704227). Cesar A. Salinas-Zavala gratefully acknowledge financial support from the Consejo Nacional de Ciencia y Tecnología Project “Aseguramiento alimentario en México: contribución de la proteína de origen marino al mejoramiento de la dieta del mexicano”. We deeply appreciate the kind comments of Dr. Juan Carlos Seijo and the anonymous reviewers that kindly contributed to the improvement of this manuscript.

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Tables

Table 1. Total costs per vessel for the proposed dwarf hake fishery off Baja California Sur west coast.

Cost	Units	Cost (USD)
Variable costs (VC)	Total VC	$55,524
		(%)
	Fuel	53%
	Oil	3%
	Wages	34%
	Food	4%
	Consumable materials	6%
Fixed costs (FC)	Assumed to be covered by the shrimp fishery	$0
Opportunity costs of labor (OC)	Crew members revenues per ship with minimum wages during hake fishing season (three months)	$6,625

Note: Costs considered five trips per season and five effective days per trip. Cost of the annual round trip Mazatlan-Bahía Magdalena is included as diesel cost for a 450 HP shrimp vessel, size of crew = 7 (Almendarez Hernández, 2013). Federal minimum daily wages= 10.37 USD (DOF, 2022). $1 USD= $20 MX

Table 2. Parameters used for the age-structured bioeconomic model for the proposed new dwarf hake fishery off the Baja California Sur west coast.

Parameter	Symbol	Value	Units	Source
Maximum standard length	L_∞	28.23	cm	Mora-Zamacona et al., submitted
Growth parameter	k	0.251	1/year	Mora-Zamacona et al., submitted
Origin	t_0	0.01		Mora-Zamacona et al., submitted
Length-weight relationship parameter	a	0.009	g	Salinas-Mayoral, 2018
Length-weight relationship parameter	b	2.98	g	Salinas-Mayoral, 2018
Price of sale	p	875	USD/ton	Sonora hake producers
Cost of unit effort	cu	55,524	USD/vessel/year	Estimated
Effort dynamics coefficient	φ	3.5E-06	vessel/ USD	Urías-Sotomayor et al., 2019
Discount rate	δ	0.037	1/year	Estimated
Annual swept area per vessel	a	8.89	km^2/vessel/year	Estimated
Distribution area	$area$	9209.96	km^2	Godínez-Pérez, 2013
50% retained length	$L_{50\%}$	13.50	cm	Estimated
75% retained length	$L_{75\%}$	16.28	cm	Estimated
Selectivity parameter	S_1	5.33		Estimated
Selectivity parameter	S_2	0.39		Estimated
Probability of capture	c	0.90		Set value
Unfished spawning stock biomass	S_0	126,177		Estimated
Unfished recruitment	R_0	1,131,055,585	1/year	Estimated
Steepness	h	0.65		Grandin et al., 2020

Table 3. Range of parameter values considered for the Monte Carlo analysis.

Parameter	Symbol	Value			Source
		Min	Intermediate	Max	
Steepness	h	0.5	0.65	0.8	Grandin et al. 2020
Price (USD/ton)	p	$750	$875	$1,000	Sonora hake producers
Maximum SL (cm)	L_∞	27.6	28.236	28.9	Mora-Zamacona *et al.,* submitted
Growth parameter	k	0.238	0.251	0.266	Mora-Zamacona *et al.,* submitted
Effort dynamics coefficient	φ	3.15E-06	3.50E-06	3.85E-06	Urías-Sotomayor, et al. 2019
Unfished recruitment	R_0	1.02E+09	1.13E+09	1.24E+09	Estimated (±10%)

Table 4. Theil's inequality coefficient values obtained in the validation of the bioeconomic age structured model, comparing estimated CPUE with the observed prospective CPUE. The threshold value is *U*= 0.2.

Symbol	Description	Value
U	Inequality coefficient	0.123
U_B	Bias proportion	0.278
U_V	Variance proportion	0.568
U_C	Covariance proportion	0.006

Table 5. Risk of falling below fishery reference points and simulated values of biomass, profits and effort levels obtained from the Monte Carlo Analysis.

Strategy	Risk of falling below LRP	Risk of falling below TRP	B_{50}/B_0			π/vessel year^{-1} (US$ thousands)			NPV (US$ millions)			Effort (vessels)		
			Lower CI	Median	Upper CI	Lower CI	Median	Upper CI	Lower CI	Median	Upper CI	Lower CI	Median	Upper CI
f_{20}	0%	0%	0.765	0.875	1.014	$92.58	$127.78	$167.34	$17.89	$28.80	$40.70		20	
f_{80}	6%	94%	0.482	0.578	0.688	$23.22	$46.95	$73.65	$22.77	$46.90	$81.70		80	
$TAC_{k2/3}f_{80}$	0%	27%	0.55	0.728	0.889	$6.36	$14.63	$22.49	$14.62	$28.43	$43.60		80	
$TAC_{k1/2}f_{120}$	33%	80%	0.35	0.551	0.764	-$0.02	$6.61	$14.07	$13.51	$26.33	$45.52	117	120	120
OA	100%	100%	0.33	0.383	0.44	-$1.91	-$0.26	$0.53	$13.37	$22.87	$34.67	110	155	200

Figure legends

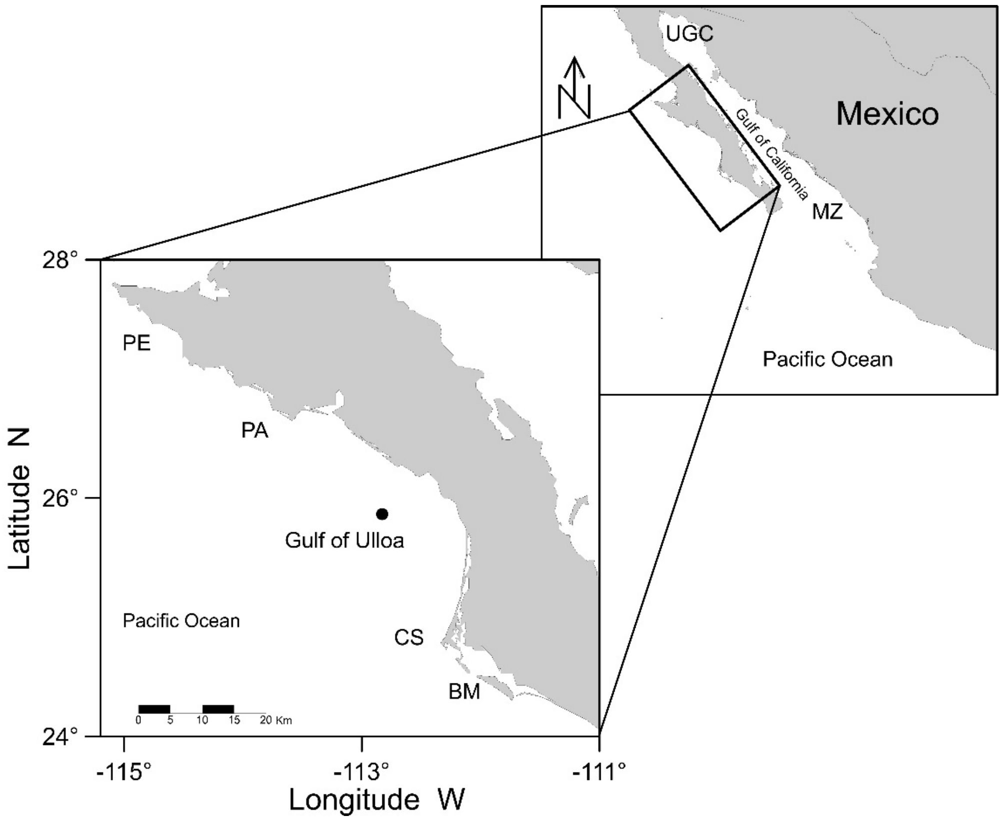
Figure 1. Gulf of Ulloa, B.C.S. Mexico, study area of present work and surveyed area by (Godínez-Pérez, 2013). PE, Punta Eugenia; PA, Punta Abreojos; CS, Cabo San Lazaro; BM, Bahia Magdalena; and MZ, Mazatlan, UGC, Upper Gulf of California.

Figure 2. Natural mortality rates at age estimated with the Chen and Watanabe (1989) method.

Figure 3. Dynamics of stock biomass, fishery yields, profits per vessel and effort levels during 50 years of operation, under five different management strategies. Trajectories obtained under the median values of the model parameters described in Table 2.

Figure 4. Risk of falling below fishery reference points and box-and-whiskers plots of proportion of the unfished biomass remaining, annual profits per vessel and number of vessels in the fishery. The horizontal line in the middle of each box indicates the median value (50th percentile), the borders of the boxes mark the 75th and 25th percentiles, and the whiskers mark the minimum and maximum values. Simulation was carried out under biologic and economic parameters uncertainty for a period of 50 years.

678 **Figures**



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680 Figure 1

681

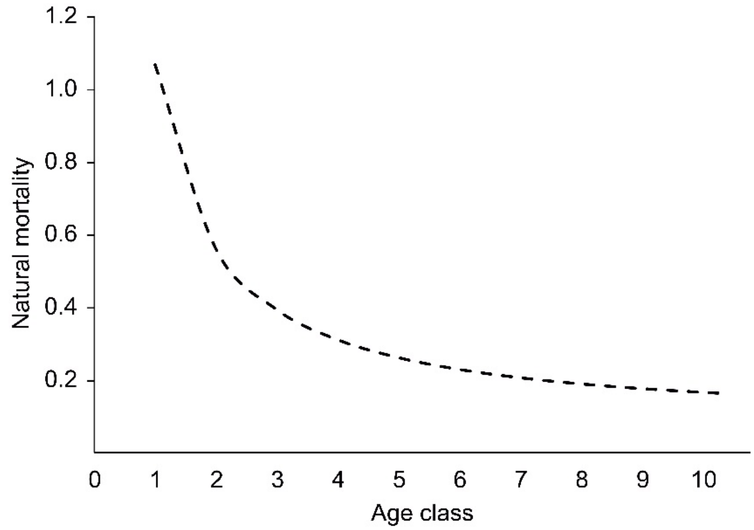

Figure 2

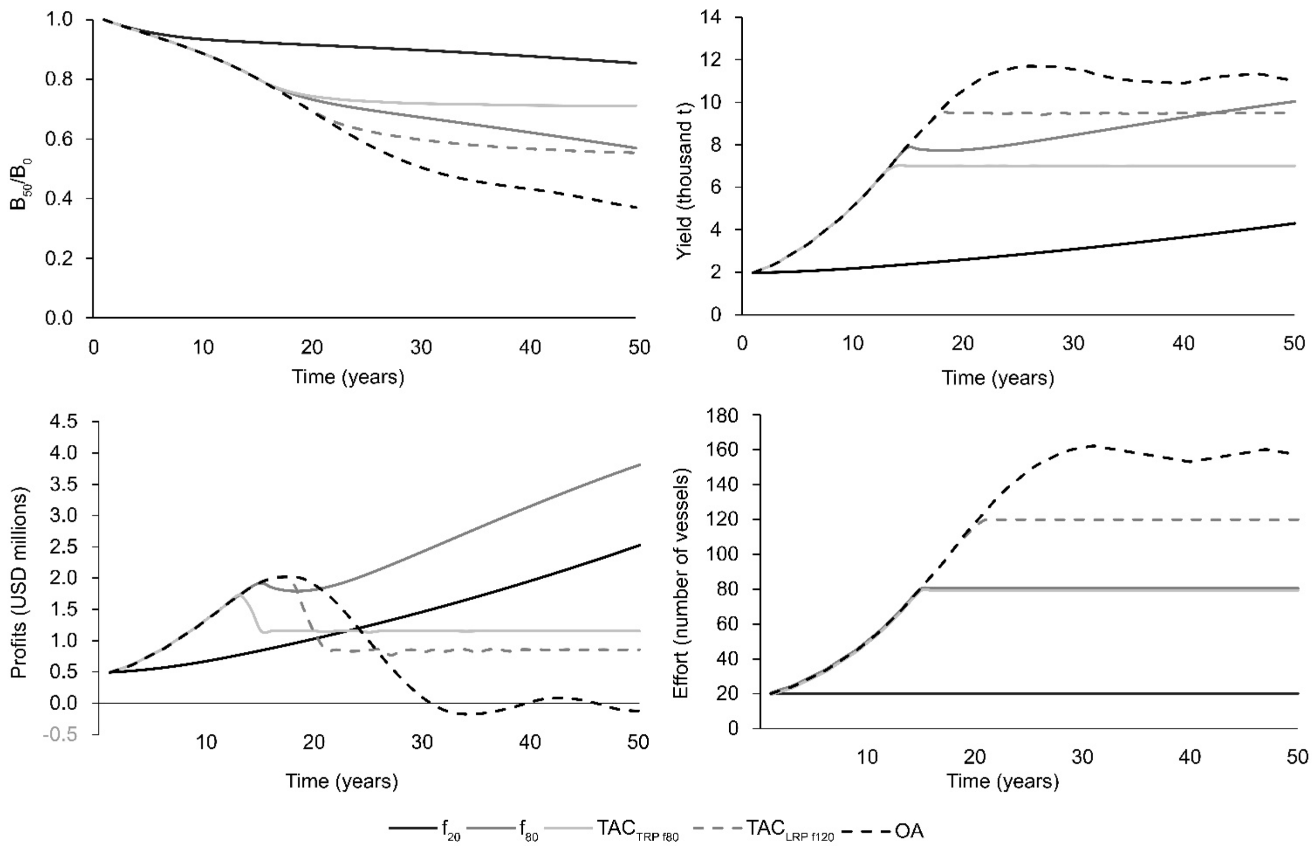
B50/B0
Time (years)
Yield (thousand t)
Time (years)
Profits (USD millions)
Time (years)
Effort (number of vessels)
Time (years)
f20
f80
TACTRP f80
TACLRP f120
OA

Figure 3

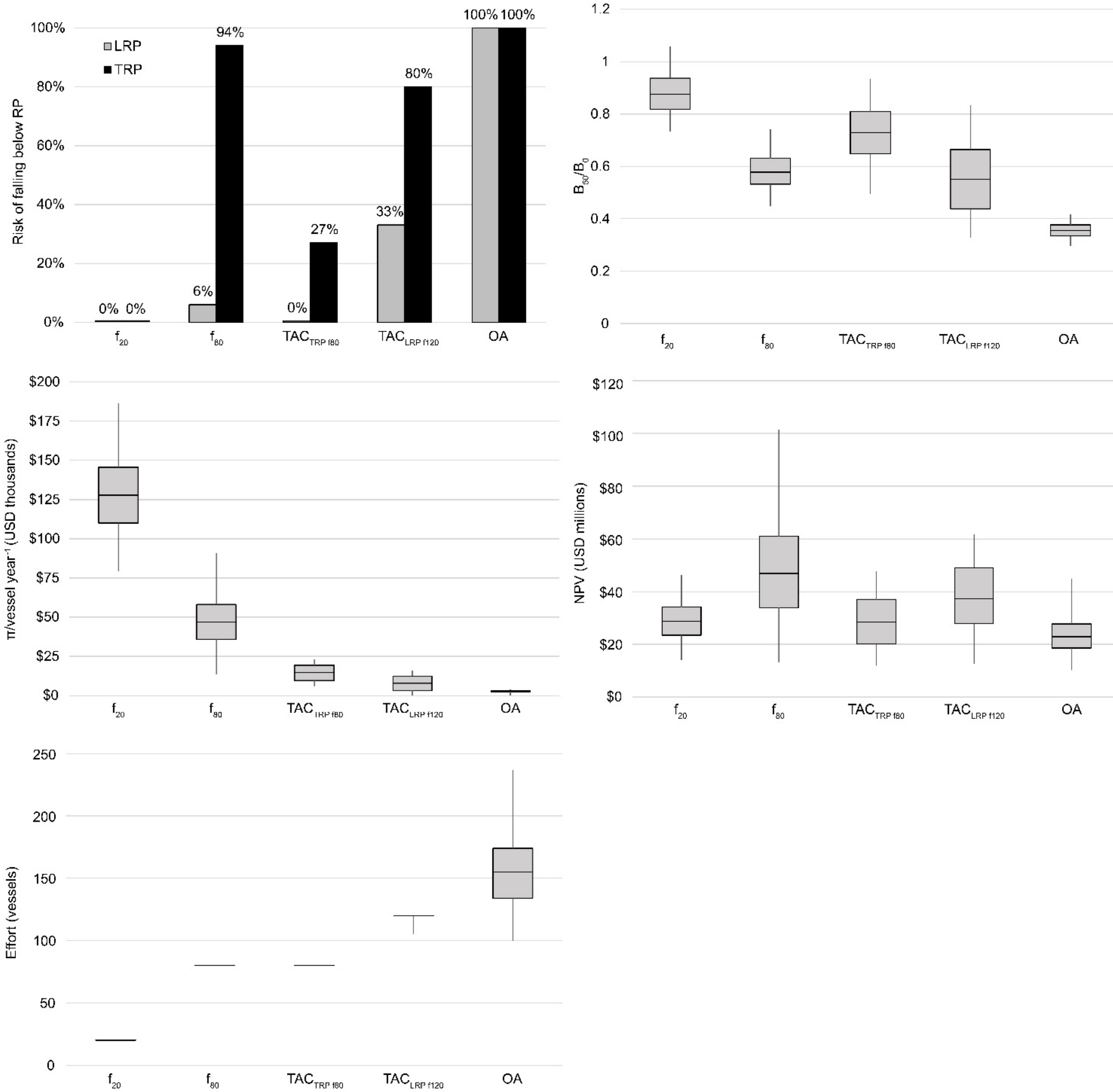
100%
80%
60%
40%
20%
0%
Risk of falling below RP
LRP
TRP
0% 0%
6%
94%
0%
27%
33%
80%
100% 100%
f20
f80
TACTRP f80
TACLRP f120
OA
1.2
1
0.8
0.6
0.4
0.2
0
B50/B0
$200
$175
$150
$125
$100
$75
$50
$25
$0
π/vessel year-1 (USD thousands)
$120
$100
$80
$60
$40
$20
$0
NPV (USD millions)
250
200
150
100
50
0
Effort (vessels)

Figure 4