grocentre.is/ftp Final Project 2022

STOCK ASSESSMENT OF THE CARIBBEAN SPINY LOBSTER (*PANULIRUS ARGUS*) IN BELIZE

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ABSTRACT

The Caribbean spiny lobster fishery is Belize's most important fishery and one of the main sources of export revenue. Therefore, properly managing the sustainability of the fishery is pivotal for the country and the people of Belize. Virtual Population Analysis (VPA) was used to reconstruct the population based on the age composition and estimated fishing mortality. VPA was tuned using the catch per unit effort (CPUE) time series. The analysis revealed that the Belize lobster population is heavily exploited, with a reduced number of lobsters reaching a large size in the population. Fishing mortality for two-year-old lobsters fluctuated between 0.5 and 1, with an average of 0.6 during the last five years. In this fishery, two-year-old lobsters are only partially selected. Fishing mortality was much higher for three- to five-year-old lobsters (approximately 2.6). The Caribbean spiny lobster yield has increased since 2015 owing to increased recruitment and a lower exploitation rate. The yield could be increased by increasing the minimum harvestable carapace length from 76 to 100 mm. There is a need to control and/or reduce fishing efforts to ensure the sustainability of the lobster fishery.

Keywords: Caribbean spiny lobster, virtual population analysis (VPA), fishing mortality, catch per unit effort (CPUE), Belize.

This paper should be cited as: Quiroz, A. D. 2023. *Stock assessment of the Caribbean spiny lobster (Panulirus argus) in Belize.* GRÓ Fisheries Training Programme under the auspices of UNESCO, Iceland. Final project.
https://www.grocentre.is/static/gro/publication/1816/document/Quiroz22prf.pdf

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1 INTRODUCTION

Belize has a total area of 22,965 km^2, including 68,894 km^2 of islands, and is situated between 15°52'9" to 18°29'55"N and 87°28" to 89°13'67"W. It shares borders with Mexico to the north, Guatemala to the west and south, and the Caribbean Sea to the east (Alford, 2022). The country's coastline is 174 miles (280 km) long and has a 269 kilometre long barrier reef with a shallow lagoon and three offshore atolls with shallow inner lagoons that provide an adequate habitat for species of commercial and ecological value, such as the Caribbean spiny lobster, Queen conch, sharks, and finfish (Alford, 2022).

Small-scale fisheries contribute significantly to nutrition, food security, sustainable livelihoods, and poverty alleviation in developing countries, yet they remain poorly understood and valued (FAO, 2004). The fishing industry in Belize is characterised as a small-scale and artisanal fishery that employs approximately 3,000 fishers originating from 13 coastal communities with over 800 fishing vessels (Licencing Unit, Belize Fisheries Department, 2022). Belize’s marine fisheries sector relies mostly on the exports of two commercial species: Caribbean spiny lobster (*Paulinus argus*) and Queen conch (*Strombus gigas*).

According to the Fisheries Department in 2021, these exported commodities were valued at $25.5 million US dollars (Belize Fisheries Department, 2021) and contributed approximately 0.5% of the Gross Domestic Product (GDP) in 2021 (Statistical Institute of Belize, 2021). Two Fishermen Cooperatives remain operational: the Northern Fishermen Cooperative Society Limited and the National Producers Cooperative Society Limited. There are also two fishing companies, Fein Catch Limited and Rainforest Seafoods Company (Belize) Limited, which continue to dominate the catch landings and exports of the main fishery commodities.

The Caribbean spiny lobster has been considered a meta-population due to its wide distribution and larval dispersion, which means that it should be managed jointly by all surrounding countries with lobster fisheries (Seijo, 2007; FAO, 2001). In 2009, Central American countries, including Belize, signed the Regulation for the Regional Management of the Caribbean Spiny Lobster Fishery (OSP-02-09) which required countries to adopt the necessary legislative changes to reflect this binding agreement. Belize’s closed season is in accordance with the harmonised regional lobster regulation (OSP-02-09) implemented by the Organization for Central American Fisheries and Aquaculture Sector (OSPESCA). In 2015, the St. George's Declaration on Conservation, Management and Sustainable use of the Caribbean Spiny Lobster

(*Panulirus Argus*) was adopted to ensure long-term conservation and sustainable use of the lobster resources from the 17 CARICOM/CRFM states.

To supplement existing management tools, such as regulations that establish size limits, weight limits, and closed seasons, Belize has increased its management efforts by implementing innovative fisheries management tools that use rights-based approaches, such as managed access (ending open access as of 2016). This has helped the Belize fishery resist the decline in the face of increased fishers in open water (Martinez et al., 2017). The lobster fishery is one of the most important marine artisanal fisheries in Belize. However, fisheries face several challenges, including increased fishing pressure, illegal activity in the eight fishing zones (Figure 1), and an outdated management plan that causes the fishery to be managed inefficiently and weakens the existing management tools.

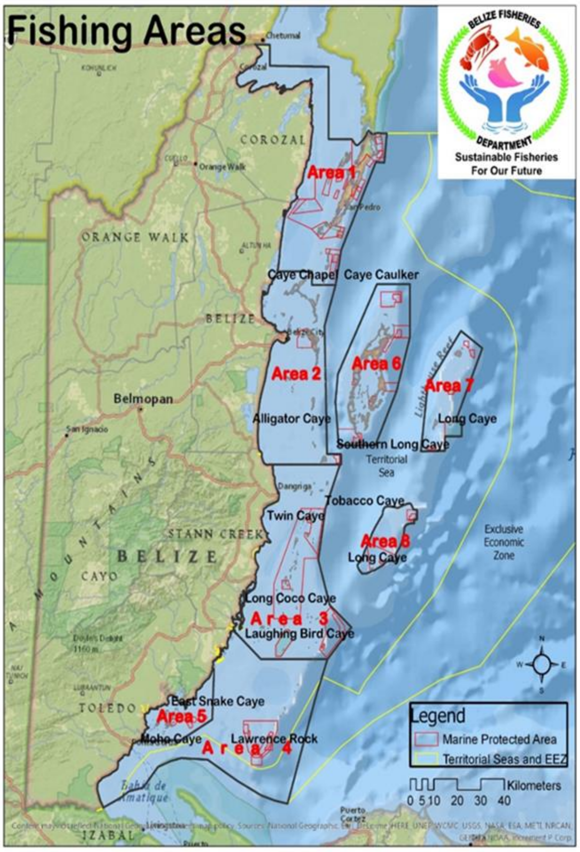

Figure 1 Fishing areas along the coast of Belize (Belize Fisheries Department, 2017).

Past stock assessments and preliminary analyses have revealed that the spiny lobster fishery is not adequately understood and has been heavily exploited. To avoid overfishing, it is critical to institute a monitoring programme to regularly assess the optimal fishing effort and MSY of the Caribbean spiny lobster stock, so that the fishing quota can be adjusted, allowing for maximum sustainable extraction while adhering to regional regulations.

1.1 Study Goals

The overarching goal of this study was to conduct a stock assessment of the Caribbean spiny lobster (*Panulirus argus)* for sustainable management of the lobster fishery in Belize by running a virtual population analysis with a simple tuning technique using CPUE based on lobster fishery-dependent data (period 1999-2021).

2 LITERATURE REVIEW

2.1 Geographic Distribution and Habitat

The Caribbean spiny lobster (*Panulirus argus*) is a valuable fishery resource throughout its range, extending from the southeastern shelf of the United States of America, the Gulf of Mexico, the continental shelf of the Bahamas, to Rio de Janeiro, Brazil, and includes the chain of Caribbean islands from Cuba to the Lesser Antilles, and the Mexican and Central American Caribbean coasts. Spiny lobster habitats are extremely diverse and contain various reef types, from shallow waters to the deep sea, extensive stretches of seagrass meadows, atolls, and mangrove swamps. Shallow seagrass beds and reefs in the Caribbean provide shelter, feeding grounds, and breeding sites for lobsters (Augustyn, 2019).

2.2 Biology of Caribbean Spiny Lobster (Panulirus argus)

The distribution and dispersal of *P. argus* are determined by four stages of the life cycle of the spiny lobster: planktonic phyllosoma larvae, swimming post-larval pueruli, benthic juveniles, and adults (Marx and Herrnkind, 1986). Its life cycle is complex and includes a long oceanic larval phase estimated at 4-7 months (Dennis et al., 2001). Once the larvae reach a certain maturity level, they settle on the ocean floor, where they live, until they are ready to reproduce (Crawford and De Smidt, 1922; Marx and Herrnkind, 1986). In general, spiny lobsters reach sexual maturity at carapace lengths of approximately 70-80 mm (2.8-3.2 inches). Females are ready to lay eggs around five years of age, but it takes them only around two years to reach the permissible harvesting size. Mature and old lobsters are usually found in deeper waters, whereas juveniles are found near mangroves, shallow sea grass beds, and coral reefs. Lobsters caught in shallow water weigh on average 0.45 kg and are approximately 25 cm longer than those caught in deeper water, which weigh approximately 2.5 kg. Spiny lobsters may live for up to 15 years and can reach at least 15 pounds and 18 inches (Witham et al. 1968, Olsen et al. 1975, Davis 1979).

2.3 The Caribbean Spiny Lobster Fishery in Belize

2.3.1 Gears and Fishing Methods

The Belizean spiny lobster fishery is exclusively artisanal, and the lobsters are caught throughout the inner reef system of the Barrier Reef using wooden traps, shades (Cuban houses), and by freediving. The lobsters are caught at depths ranging from 1.5 to 27 m along the reef barrier, coral reefs, reef patches, and in three 3 offshore atolls (Cárcamo, 2019). Approximately 800 fishing vessels are operational in the fishing areas of Belize, which fish for lobsters. These vessels (skiffs) are motorised vessels ranging in size from 15 to 30 ft with a crew of 3-5 fishers onboard for 3–4-day fishing trips (Figure 2). It is important to note that scuba fishing is prohibited in Belize.

Figure 2 Fishing Vessel (skiff) (Aldana, 2021).

In addition, traditional wooden sailboats of 6-10m (Figure 3a) are equipped with sails and auxiliary engines. These boats carry up to 10 small canoes and 10 divers for a 5–10-day fishing trip (Figure 3b).

Figure 3 Traditional wooden sailboat (a) and auxiliary vessel – canoe (b) Aldana, 2021.

Lobsters are harvested by free-diving to a maximum depth of 18-21m using hook sticks or traps (Ylitalo-Ward et al., 2016). The design of the trap is shaped like a trapezoid and is traditionally made of a hardwood frame with strips of "pimento" (*Acoelorraphe wrightii*) wood for the body of the trap and at the first and second strip of the lateral side of the trap, an escape gap, the width of 1 inch (Figure 4a). Similarly, some fishers use lobster shades, or casitas, to lure lobsters. These are made of a sheet of zinc that creates shade under which lobsters hide and congregate (Figure 4b) (Belize Fisheries Department, 2019).

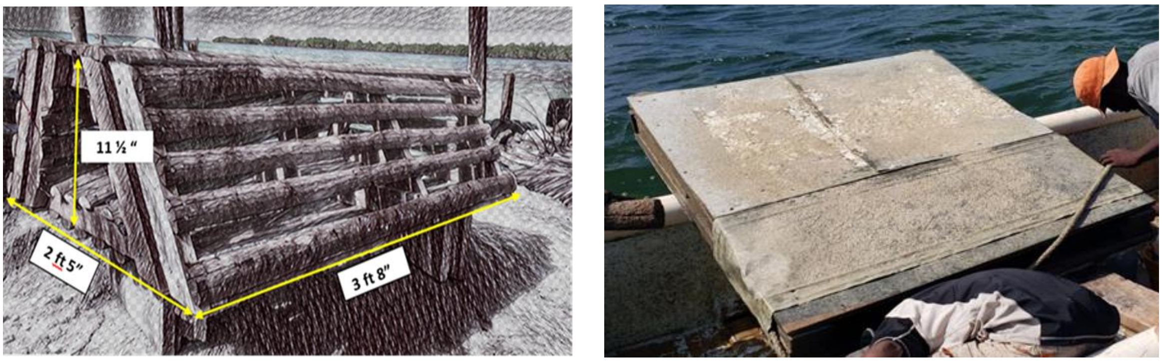

Figure 4 (a) Wooden trapezoid lobster trap (Fisheries Department, 2018) and (b) lobster shade or casitas (Aldana, 2021).

2.4 Status of the lobster fishery

Over the past few years, the lobster fishery has dominated the small-scale fishing industry in Belize as one of the most important income earners. On average (200-300 tons) of lobster tails are exported annually. The fishery is a seasonal fishery that is open for only eight months every year. Lobster tails and whole lobsters are landed at cooperatives equipped with a processing plant (Fisheries Department 2021, unpublished). Fishing cooperatives play a significant role in the development of the fishing industry and are owned and operated by fishermen (Gongora, 2010).

According to the Fisheries Department, lobster production has shown a general increasing trend from 181.4 MT in 2006 to over 317.5 MT in 2021 (Fisheries, Department, 2021), with fishing effort gradually increasing over time. The fishery has been classified as a mature, stable fishery with no real possibility of increased catch in the current fishing areas. Recently, fishing cooperatives have diversified commodities into whole lobsters, increasing the total number of lobsters landed. According to the Fisheries Department, lobster production was 1070.3 MT in 2021, a 6% increase compared to 2020 (1009.43 MT whole weight). The lobster fishery's estimated value was 17.7 million USD in 2021, representing a 37% increase compared to 2020 (12.9 million USD) (Fisheries, Department, 2021).

2.5 Caribbean spiny lobster capture by country

According to FAO (2018), 286,765 tons of Caribbean spiny lobster (live weight) were captured in FAO area 31 between 2007 and 2016. Within this capture area, the Bahamas has the highest catch (76 thousand tons), followed by Cuba, Honduras, and Nicaragua (45-46 thousand tons) (Figure 5).

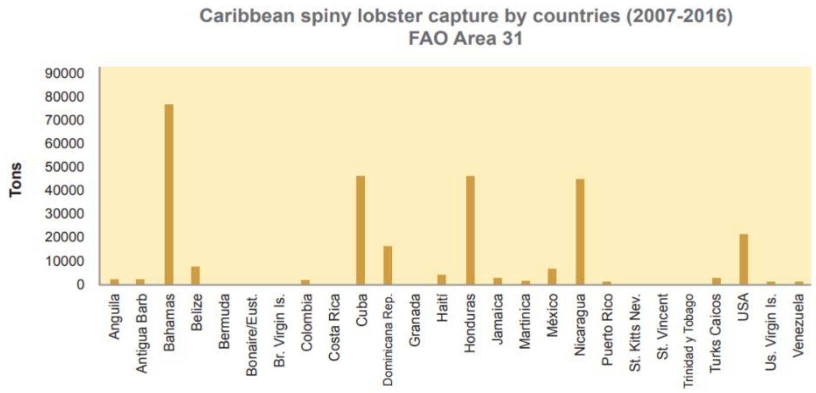

Figure 5 Caribbean spiny lobster capture production (tons) by Caribbean countries (FAO 2018).

2.6 Management of the spiny lobster fishery in Belize

The Belize Fisheries Department is tasked with sustainably managing the fishing industry. The Fisheries Department technical arm is mandated to properly implement innovative management tools such as the management access program, which is a rights-based approach to fisheries management that aims to ensure fisheries sustainability by proactively incorporating fishers to participate in management decisions and submit fisheries catch landing data.

2.6.1 Belize Fisheries Regulation

The Fisheries Act of 1948 and its amendments, regulations, and subsidiary legislations were enacted in 1977 and are applicable to both marine and inland waters. These regulations provide a legal framework for fisheries management and the law enforcement functions of the Belize Fisheries Department (BFD). They include regulations on minimum size limits, closed fishing seasons, marine reserves, and regulations for spiny lobster (*Panulirus argus*), queen conch (*Strombus gigas*), marine shrimp (all marine species), sharks, Nassau grouper (*Epinephelus* *striatus*) and a freshwater turtle locally known as Hicatee (*Dermatemys mawii*). Fisheries regulations prohibit commercial fishing using SCUBA gear. These regulations also prohibit the capture and possession of marine turtles, whale sharks, bonefish, and corals.

Fishing for lobsters is regulated by the Fisheries Resource Act which was revised in 2020 and enacted in October 2021 with the effect of the Statutory Instrument 128 of 2021 on 1 March 2021, (which included changing the closed season from 15 February -14 June to 1 March–30 June, to match the Organization of the Fisheries and Aquaculture Sector of Central America (OSPESCA)). It also changed size limits of carapace length from 3 to 3.25 inches and tail weight from 4 to 4.5 oz, but these changes are not implemented, pending further studies (Fisheries (Amendment) Regulation, 2021).

2.6.2 Regional Regulations for the Caribbean Spiny Lobster

The MARPLESCA plan contains valuable contributions such as the "Subregional Management of the Caribbean Spiny Lobster Fishery (*Panulirus argus*)" of the first CLME project to develop a management plan for the spiny lobster fishery in the Caribbean for the Central American Integration System (SICA) member states. Increased regional cooperation has led to other management tools such as the 1 July 2009 binding Regulation for the Regional Management of the Caribbean Lobster Fishery OSP-02-09. Additionally, in 2015, St. George's Declaration was adopted in the framework of the CRFM/CARICOM. The objective of the MARPLESCA plan is to establish a systematic process for the Caribbean spiny lobster fishery in several countries for fisheries management within a sustainable exploitation framework that promotes ecological balance and social and economic benefits for stakeholders (OSPESCA, 2018).

The plan addresses the following:

- Strengthen the effective application of the OSPESCA Regulation OSP-02-09 and CARICOM St. George's Declaration and WECAFC recommendations.
- Coordination and participatory management of Caribbean spiny lobster fisheries with regional coverage under the SICA/OSPESCA, CARICOM/CRFM, and WECAFC governance models.
- Promote appropriate organisation for the institutionalised participation of key stakeholders in fisheries management.
- To create conditions for the adoption and implementation of the plan in the geographical range of the Caribbean spiny lobster (*Panulirus argus*) under the CLME+ Strategic Action Program (SAP).

In 2009, Central American countries, including Belize, signed the Regulation for the Regional Management of the Caribbean Spiny Lobster Fishery (OSP-02-09), which requires countries to make the necessary legislative changes to implement this binding agreement. Belize's closed season is consistent with the harmonised regional lobster regulation (OSP-02-09) implemented by the Organization for Central American Fisheries and Aquaculture Sector (OSPESCA). The objective of the current regulation is (OSPESCA, 2009):

1. Establish binding measures which allow the harmonisation of the regulation and management of the Spiny Caribbean Lobster in the region.
2. Ensure appropriate management and sustainable use of this resource based on responsible fishing.
3. Recover, protect, and use the Caribbean spiny lobster fishery sustainably.

Management measures for the Caribbean Spiny Lobster (*P. argus*) Fishery by the OSP-0209 regulation are as follows:

- **Article 4.** Closure.
  Beginning in 2010, the states agreed to suspend the whole Caribbean spiny lobster (*Panulirus argus*) fishery for four months, from March 1st to June 30th of each year.
- **Article 5.** Number of traps.
  The maximum number of traps allowed per industrial vessel in fishing is two thousand five hundred (2,500). In the case of artisanal fishing, the government of each nation will establish a number of traps based on technological research. The materials used to construct traps must be biodegradable.
- **Article 6.** Escaping gap.
  Traps must contain at least one escape gap on the opposite side of the line used to hoist the trap, with an escaping aperture of 21/8 inch (5.4 cm) between the bottom and the first rib from the bottom above, to ensure the evacuation of young lobsters.
- **Article 7.** Placement and removal of traps.
  Before the commencement of the closure, persons and legal entities authorised to practice this fishery are obliged to remove traps from the sea. Fishery Authorities shall authorise the removal of traps placed once the closure has commenced, only when an inspector on board ensures the return of the caught product to the sea. States may authorise the placement of traps on fishing grounds ten days before the end of the closure period.
- **Article 8**. Inventories.

State Parties shall adopt relevant provisions requiring vessel owners, processors, and traders to submit to the competent authority the inventory or availability of lobsters in their possession by the third day of the closure, which shall be the sole quantity that can be marketed during the closure period. The responsible authority must verify the inventory within five days of receipt. Regardless of any other control provisions that each State Party may apply, the competent authority may conduct inspections, as it considers necessary.

- **Article 9.** Sailing permits.

  During the closure, the competent authority shall suspend fishing sailing permits for industrial and artisanal vessels authorised to fish for lobsters.

- **Article 10.** Navigation during closure.

  During closure, there will be no fishing activity for the lobster. In addition, vessels authorised to fish for lobsters may sail only for officially justified reasons before the responsible authority, such as maintenance, or because the competent authority permits the vessel to conduct another fishery.

- **Article 11.** Minimum size and weight.

  A minimum length of one hundred forty millimeters (140 mm) is imposed for capturing and storage purposes, measured from the first abdominal segment to the terminal section of the telson. An average weight of five ounces per unit of commercial packaging is specified for packaging and marketing reasons, with a range of 4.5 to 5.5 ounces of thawed lobster tail.

In 2015 St. George’s, Grenada, Fisheries Ministers from the member States of the Caribbean Regional Fisheries Mechanism (CRFM) attended the 9th Meeting of the Ministerial Council of the Caribbean Regional Fisheries Mechanism (CRFM), where The St. George's Declaration on Conservation, Management and Sustainable use of the Caribbean Spiny Lobster (*Panulirus Argus*) was adopted to ensure long-term conservation and sustainable use of the lobster resources from the 17 CARICOM/CRFM states. These management measures were non-binding but reflected those adopted by OSPESCA in 2009.

OSPESCA organised a regional workshop in Panama in 2017 to harmonise and validate data forms and stock assessment methods for the Caribbean spiny lobster, and to develop recommendations and post-workshop actions. Dr. Elizabeth Babcock from the University of Miami presented a stock assessment model that was used in two marine protected areas in Belize (Glover's Reef and Port Honduras). The assessment was based on a Bayesian depletion model that accounted for recruitment. However, the results of this assessment were preliminary and could not be used to determine the status of fisheries at the national level. Nevertheless, catch rates have been found to be close to sustainable fisheries levels (Babcock, 2015). Following this presentation, Mr. Ramon Carcamo (Fisheries Officer) noted that the Belizean lobster fishery can be considered highly exploited but also mentioned that there is an unexploited portion of the lobster population in deeper waters where artisanal fishers do not operate. In general, it was noted that there are issues with data quality in terms of the temporal and spatial coverage of fishing effort, resulting in conclusions that are highly unlikely to be accurate (OSPESCA, 2017).

2.6.3 Marine Protected Areas

Belize has abundant coastal waters that are vital to the survival of communities. A substantial portion of the sea is available for fishing with the condition that fishers obtain a valid fishing licence in that region. Some areas within the waters have been classified as marine-protected areas to support the sustainability of fish stocks and marine ecosystems. There are currently nine marine reserves, five of which are managed by the Fisheries Department and three reserves that have been managed under co-management agreements with local non-governmental organizations. Nonetheless, the Fisheries Department maintains the management and law enforcement duties in these reserves.

Marine reserves are divided into zones: the General Use Zone, conservation and preservation zones, and no-take zones. Fishers are permitted to fish within the general use zone which makes up 80% of reserves; however, gear regulations are in place (for instance, no spear guns or nets), and surveillance and enforcement patrols are active within this zone. Second, conservation Zones and Preservation Zones (15%) protect high-value areas, such as spawning aggregation on sites or fish nursery grounds–no-take replenishment zones. No commercial fishing is allowed in these areas. Furthermore, only 5% of Belize’s waters are protected as replenishment (no-take) areas (Marine Conservation Institute, 2022).

2.7 Review of stock Assessments of spiny lobster

According to the initial survey of lobster stock undertaken in 2005, the population of spiny lobsters in Belize appears to be extensively exploited. For the fishery, significant fishing mortality was predicted; however, the entire condition of the stock was unknown at the time because it was believed that the observed fishing mortality only pertained to a section of the stock (Belize Fisheries Department, 2005).

A second assessment used seven years of tail weight data (1999–2006) gathered from Belize's two major fishing cooperatives to conduct a cohort analysis in 2007. The Cuban tail weight-carapace length was used to convert the tail weight data to carapace lengths. According to the study's findings, 40% to 60% of the stock was taken each year, and fishing mortality (F) reached as high as 0.7 yearly (Belize Fisheries Department, 2007).

According to an assessment conducted in 2008, lobster catches stabilised between 1985 and 1995; however, since then, catches have decreased. The study also indicated that the average size of lobsters increased over time within five years. This may indicate that fishers were diving deeper to harvest adult spawning stock. There has been a significant decrease in the abundance of lobsters over the last six years. Nonetheless, there was a steady recruitment of estimated 4-year-old lobster, although in small amounts (Belize Fisheries Department, 2008).

According to Gongora (2010), an assessment of the spiny lobster fishery in Belize was conducted based on fishery-dependent lobster tail export data collected from two fishing cooperatives for 1999–2009. This assessment showed that catches consist of two age groups (ages 2 and 3), which represent approximately 98% of the catches. The catch per unit effort, stock size, and recruitment levels appear to have declined during this period. In addition, fishing mortality was high, and the fishery could be experiencing some overfishing. It was recommended that management intervene to reduce fishing efforts and increase the minimum size limit.

A preliminary stock assessment using the model proposed in the regional management plan for the Caribbean spiny lobster in Belize for the period 2010-2018 was done in 2019. The results of this evaluation indicated that the stock was subject to high fishing pressure, observed by a decrease in the average size, as well as in the catch per unit effort (CPUE). It also showed that the number of fishers and vessels in recent fishing seasons did not correspond to any increase in catch (landings), which could indicate overfishing. The analysis showed that 51% of lobsters landed and exported are of a small size (4.5- and 6-ounces tail weight) and fall within an age range of 2.5 to 3.5 years old. The number of recruits fluctuated between 700 thousand and 1 million for the period analysed (fishing season 2010-2011 to 2018-2019). It was also noted that fishing mortality was 0.56 for that fishing season. Furthermore, it is possible that the causes of the drop in fishing performance are not only attributable to fishing exploitation but also to changes in habitat conditions, water temperature, and extreme climatic circumstances (hurricanes), among others (Puga et al., 2007). The report made key management recommendations which included limiting fishing effort, improving regulations, establishing a national catch quota, and conducting a more comprehensive assessment using the model based on the MARPLESCA plan in 2019.

2.8 Stock Assessment Method - Virtual Population Analysis

According to the virtual population analysis manual, "a stock development is based on several processes, such as growth calculated using the von Bertalanffy model; however, stock development often can be described as an age group vector of mean weight per individual. Second, recruitment is described as a function of spawning stock biomass only:

$$R = R(SSB);$$

$$\text{Survival} = N_{age+\otimes t} = N_{age}\, e^{-Z \otimes t}$$

The total mortality Z is decomposed into fishing mortality (F) and natural mortality (M) as $Z = F + M$, where fishing mortality *(F)* is assumed to be an independent process of natural mortality (M). Natural mortality is either an age-dependent fixed parameter where M=M(age) or a multispecies interactive process as in: M = M(age, other populations)." (Lassen, H.; Medley, P, 2001).

According to Gulland (1965), virtual population analysis (VPA) became useful when the Baranov catch equation incorporating observed catches could be solved sequentially. This method requires age structured data. It provides an estimate of cohort recruitment for that fishery and is a helpful exploratory data analysis technique for heavily exploited fish stocks. Furthermore, provided that the exploitation rate is high in comparison to the natural mortality, it also provides an estimate of fishing mortality for years that are dominated by cohorts that have passed through. Catch-at-age data were derived from large-scale size frequency sampling, and smaller-scale age sampling to provide age-length keys. Alternatively, the age distribution can be obtained directly by sampling the catches and aging the entire sample, although often it is difficult to get good coverage at a low cost. The VPA model was built on the assumption that there is one cohort per year, but the model requires modifications when there are several cohorts per year. There are examples in which there is no cohort structure in the population, because the fish stock spawns continuously. The population model applicable to such a situation differs from that applied in this manual. The model is made up of the total catch in number by age and year; abundance estimates in absolute terms, each index representing one or several ages and indices; biomass indices; effort indices, and the mean weights by age and by year corresponding to the catch (Gulland, 1965).

3 METHODOLOGY

3.1 Source of Data

Two fishery-dependent datasets were used in this study, including historical records of lobster tail landings and exports by weight for the time period–1999-2021 and catch per unit effort (CPUE) data for 2000-2016 from catch logbooks and purchase receipts submitted by fishers as well as the Tally System from the National Cooperative (2018-2021).

The Tally System is an electronic seafood traceability system that allows collection of landing data in real time at the reception point. This system aims to reduce operational costs by modernising management processes and creating a data-rich fishery that supports effective co-management and conservation. This is a form of transition to traceability and moves away from paper data collection. This system uses tablets to track all landed products (shellfish and lobster) and record the date, name of the fisher and vessel, type of product, total weight, fishing area (areas), gear type, and effort.

Export data were obtained from historical records for the period–1999-2021 from exporting fishing cooperatives in Belize (see Appendix Table 1). Methods similar to those used in the 2010 spiny lobster stock assessment were used in this study (Gongora, 2010). The data were compiled in a Microsoft Excel spreadsheet and converted to metric tons per year. Subsequently, the data were imported into RStudio for statistical analyses. Lobster tail weights were converted to ounces, and the number of individuals was calculated by dividing the exported weight by the appropriate commercial weight classes: 4, 5, 6, 7, 8 ounces, 10-12 ounces, 12-14 ounces, 14-16 ounces, 16-20 ounces, 20-24 ounces and > 24 ounces (Appendix Table 2). These size categories (TW) were converted to grams and carapace lengths were calculated using the following relationship:

$$CL = 16.31 * TW^{0.311}$$

(Wade et al.1992; Gongora, 2010).

Subsequently, the age classes for each carapace length were estimated using the Von Bertalanffy growth model:

$$L_{(t)} = L_{\infty} * [1 - exp\ exp\ (-k^\wedge(t - t_0))\ ]$$

Growth parameters (L∞ = 183 mm, k = 0.24, and t0 = 0.44) were used in the 2010 Belize lobster stock analysis and were similar to the values reported for southwestern Cuba (Leon et al. 1995). A natural mortality (M) value of 0.34 was used. This value was adopted from Cruz et al. (1981) because it is accepted as the average value for the spiny lobster in the Caribbean.

A matrix of catch numbers by age per year for the period 1999-2021 was created from the results of the slicing method (Sparre and Venema 1998); the same method was used in Gongora's (2010) work in Belize. First, the average length was calculated for each assigned age group. The corresponding length class for each age group is also determined. Then, the proportion in the lower groups is calculated. This proportion is the difference between the mean length at age and the minimum length of the length class, divided by the length class distance. The catch at age group was obtained by multiplying the proportion of length classes by the catch and was used as the initial data set for the virtual population analysis (Appendix Table 2).

3.1.1 Virtual population analysis (VPA)

A virtual population analysis (VPA) was used to assess the lobster stock. The calculations were performed using R studio in the FLCore and FLAssess packages. Catch-at-age numbers were obtained using the slicing method (see above). The stock and catch equations for the VPA are as follows:

Stock equation $N_{a+1,y+1} = e^{-Z_{ay}} * N_{ay}$

Catch equation $C_{ay} = \frac{F_{ay}}{Z_{ay}} * (1 - e^{-Z_{ay}}) * N_{ay}$

Here, the subscripts a and *y* refer to the age and year, respectively. The parameter N_{ay} is the population size at age *a* in year *y*, C_{ay} is the population size at age *a* in year *y*, and the parameter Z_{ay} is the total mortality at age *a* and in year *y*. The total mortality is the sum of natural mortality and fishing morality F_{ay}:

$$Z = F + M$$

where:
Z= Total Mortality
F= Fishing Mortality
M= Natural Mortality

To start the model process, the stock size in the previous year was calculated using the following equation:

$$N_{ay} = \frac{C_{ay}}{\frac{F_{ay}}{Z_{ay}}(1 - e^{-Z_{ay}})}$$

The number at age for the incomplete cohorts can be estimated using the formula below if a value of F_y and the catch at age in the last year are available.

$$N_y = \frac{C_y}{1 - e^{-Z_y}} \frac{F_y + M}{F_y}$$

Similar to numbers-at-age, if the terminal mortalities are known, the fishing mortalities for the incomplete cohorts can be calculated from the equation:

$$F_{ay} = ln\, ln \left(\frac{N_{ay}}{N_{a+1,y+1}}\right) - M$$

3.1.2 Catch per Unit Effort

The CPUE time-series was estimated using 383,547 entries for the period 2000-2022 from catch logbooks and lobster catch purchase slips at the cooperative (2000-2016), as well as from the Tally System (2018-2022). An average of five years was used for 2017 as for that specific year datasets were missing.

The index of abundance in this assessment was catch per unit effort (CPUE), which was estimated using the following equation:

$$CPUE_y = C_y/E_y$$

where:
$CPUE_y$ = catch per unit of effort in the year $_y$
E_y= Effort (days) in year *y*

3.1.3 Simple Method of Tuning Virtual Population Analysis

Virtual population analysis requires terminal estimates of fishing mortality (or harvest) in the oldest age class and most recent point in time. This dependence limits the usefulness of the method because the terminal (in age and time) estimates of fishing mortality are often the most valuable information to be conveyed to fishery managers. Additional information on catch by age and fishing effort, either from a fishery sub-component or from a fishery-independent source such as a research survey, can be used to 'tune' the assessment and thereby generate estimates of terminal fishing mortalities (and thus stock abundances) as opposed to presumed values. The Laurec-Shepherd method was used to tune VPA in this study (Shepherd, 1999). This method iterates VPA until the terminal estimates of mortality have reached a degree of stability. For this method, catchability is defined as the ratio between mortality and effort and is assumed to be constant in time, with effort constant across ages.

3.1.4 Yield per recruit

Yield per recruit was estimated from weight-at-age-weight values, a selectivity curve estimate, a natural mortality assumption, and fishing mortality. The yield for each age (Ya) was estimated by multiplying the catch by the weight at age:

$$Y_a = C_a W_a$$

Following this the yield per recruit (Y/R) was estimated:

$$\frac{Y}{R} = \sum \frac{Y_a}{R}$$

Where:

C_a= catch at age
W_a = mean weight at age
R = recruitment

4 RESULTS

4.1 Landings and CPUE

There was an increase in the number of registered fishers from 1,500 to 2,700 during the period 1996-2021, but the number of boats varied between 500 and 900 (Figure 6). The estimated landings of the spiny lobster (*P. argus*) fluctuated between 500 and 1,000 tones between 1977-2021 (Figure *6*). A peak was noted during 1981-1985 of 900-1,000 tons. Catches remained stable at 600–800 tons between 1986-2014, increasing to over 1,000 tons in recent years. It can be observed that the number of fishers increased over time, along with the total production, which might signify the possibility of higher production in lobster landings. However, this interpretation is limited by a lack of knowledge of the true fishing effort.

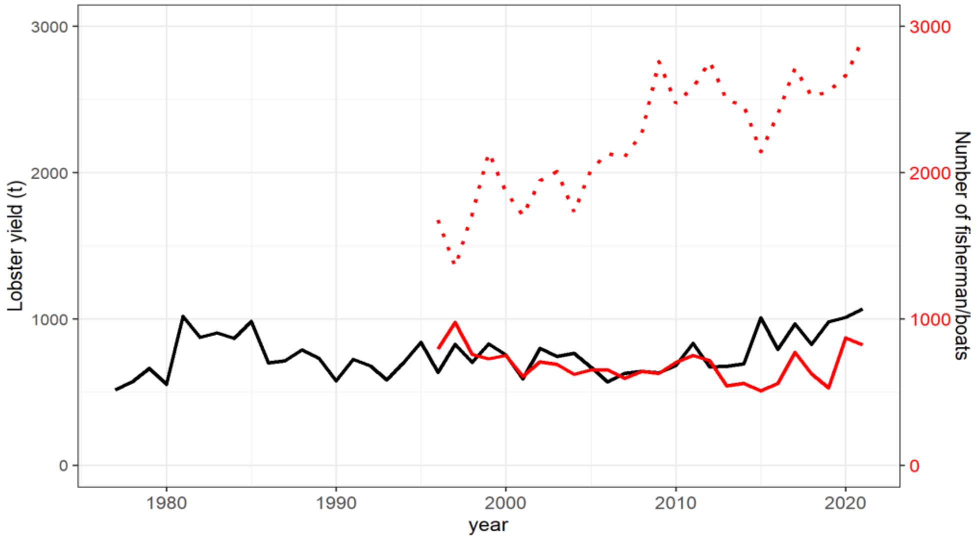

Figure 6 Landings (whole weight) of Caribbean spiny lobster (Panulirus argus) in Belize 1977-2021 (black line). Number of fishermen (dotted red line) and number of vessels (solid red line) 1996-2021.

4.1.1 Catch per Unit Effort (CPUE)

The CPUE, based on the number of registered boats, has increased over the past 25 years, with two apparent peaks in 2015 (2,000 kg) and 2019 (1,800 kg) (Figure 7). However, the CPUE based on the number of registered fishers has been relatively stable in recent years, at approximately 400 kg per year (Figure 7).

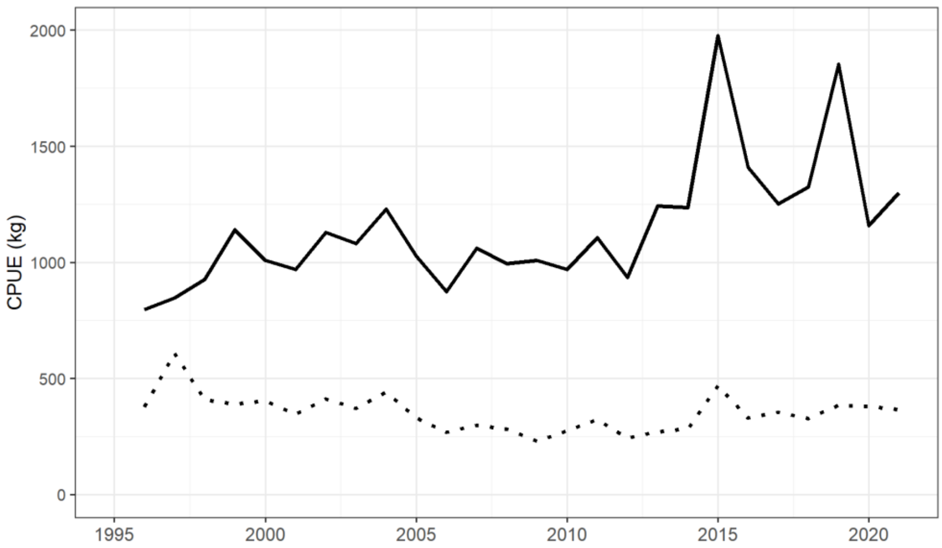

Figure 7 Estimated CPUE (kg fished) per registered fisherman (dotted line) and per vessel (solid line), during 1996-2021.

The CPUE estimated from individual fishing trips where freediving was the fishing method fluctuated from 6 to-11 lbs of tails per day in 2000-2021 (Figure 8). Information on the CPUE by individual areas and different gear types is found in the Appendix (Figures A21 and A22).

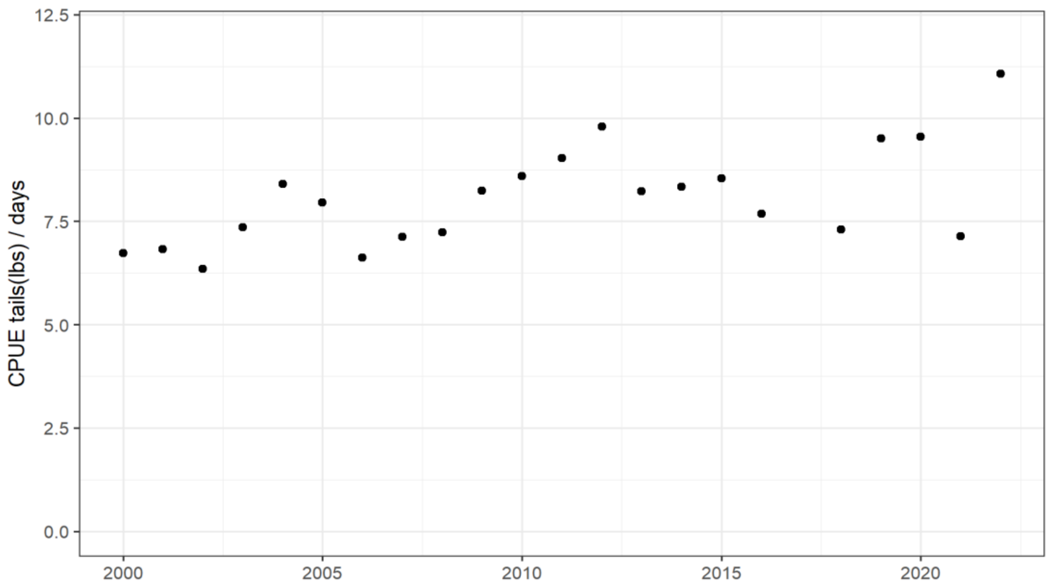

Figure 8 Estimated CPUE in tails (lbs) per day fished per boat by diving, during the period 2000-2016 and 2018-2022.

4.2 Stock Assessment

4.2.1 VPA with Tuning Technique (CPUE)

Fishing mortality for two-year-old lobsters fluctuated between 0.5 and 1 and has been around 0.6 for the past five years (Figure 9a). Two-year-old lobster are only partially selected in this fishery. The estimated fishing mortality was higher for ages 3 to 5 (2.6) but there has been a decrease in fishing mortality in 2016, with a gradual increase in recent years. The number of estimated two-year-old recruits fluctuated around 2 million until 2015 when they reached 2.5 million (Figure 9). The largest two-year old cohort was in 2017 (3.5m) and recruitment was still high in 2018-2021. Subsequently there has been an increase in the number of 3- to 5-year-olds since 2018.

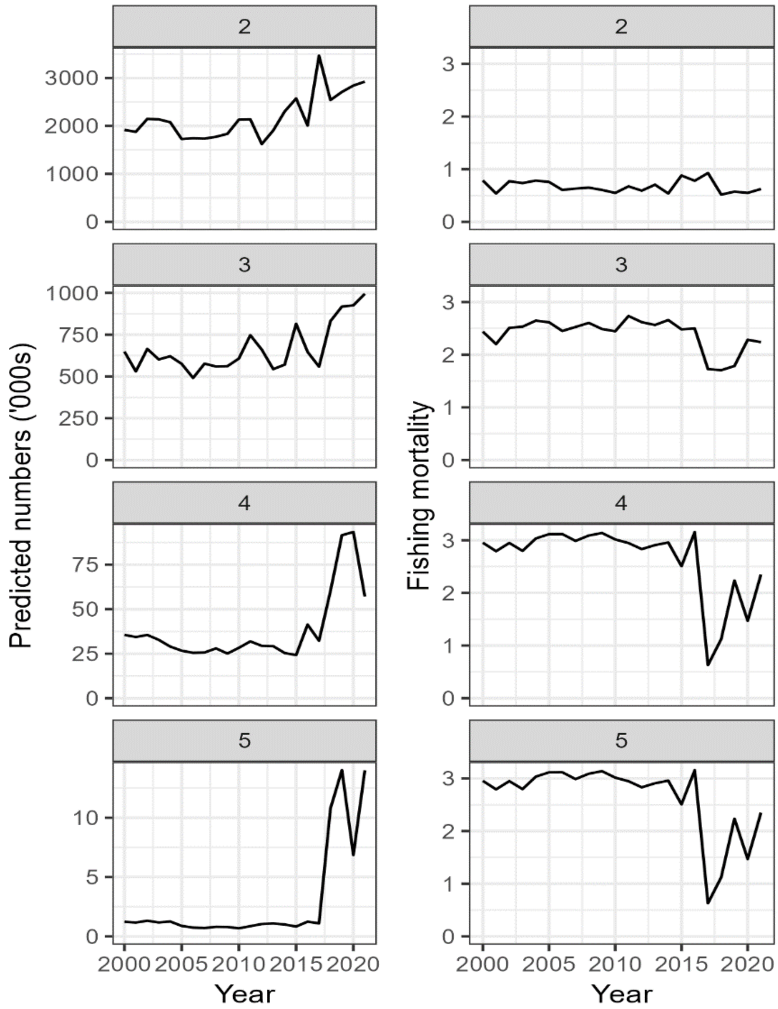

Figure 9 Predicted number at age and fishing mortality at age for the period 2000 – 2021.

The estimated total average biomass fluctuated between 400-600 tons in tail weight between the period of 2000-2021 (Figure 9b). It can be noted that there was an increase in biomass in the period 2018-2021 to 500-600 tons. In 2015, we can observe an increase in catch that is correlated with an increase in recruitment and a following increase in biomass with continuous recruitment into the lobster fishery over the recent years (Figure 10).

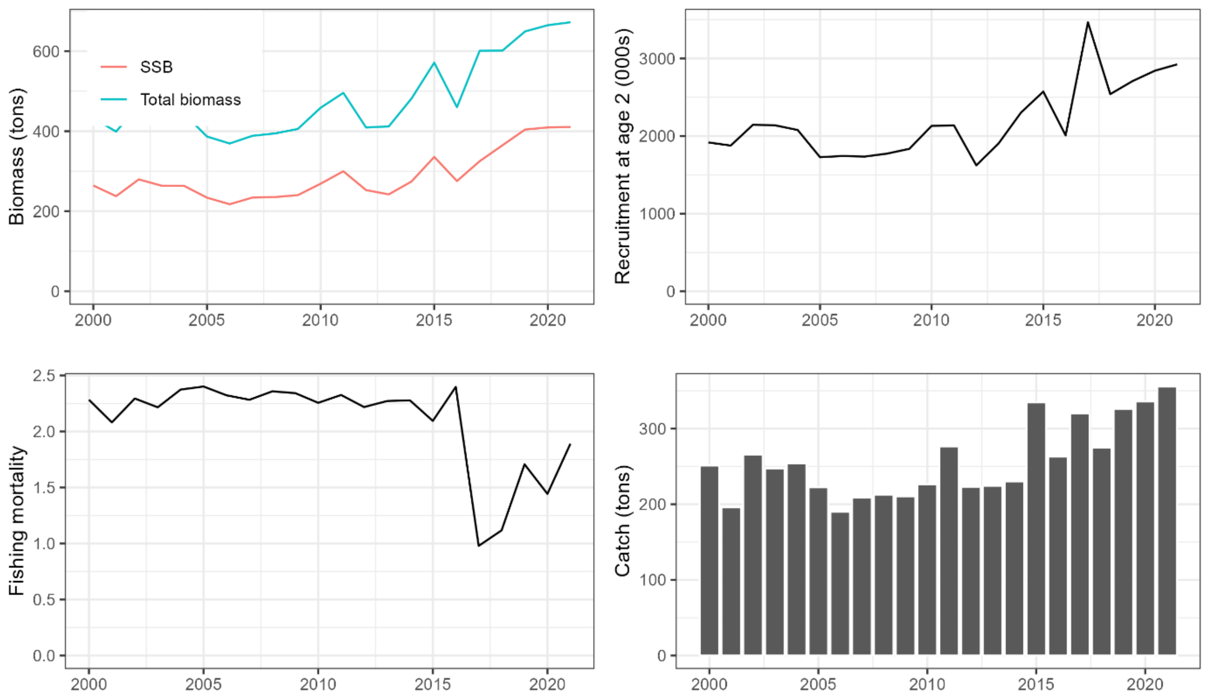

Figure 10 Estimated recruitment, biomass, fishing mortality and catch of tail weight (t) by year.

4.2.2 Yield per Recruit Analysis

Maximum yield (~76 gr) is achieved at a fishing mortality of 0.66 for the baseline scenario (size selection at 76 mm carapace length), and a natural mortality of 0.34 (Figure 11). It is proposed that increasing the selection size to 100 mm would correspond to a yield increase of more than 86 grams per recruit and to a similar level of 120 mm, but at much higher fishing mortality.

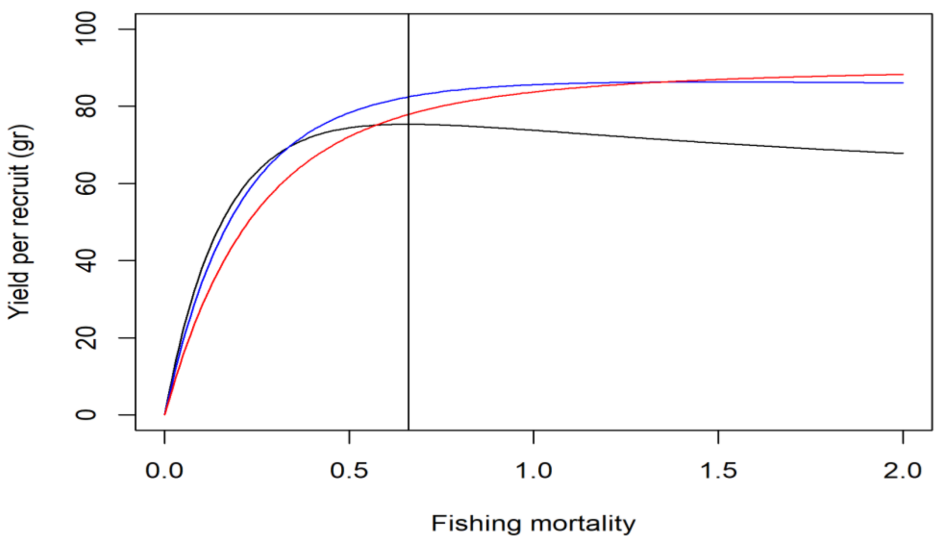

Figure 11 Yield per Recruit (gr) vs Fishing Mortality at three different carapace length size selections (black: 76 mm, blue: 100 mm, red: 120 mm).

The estimated yield per recruit was calculated for different levels of natural mortality and the same selection patterns of carapace lengths (Figure *12*). It can be observed from the graph that yield per recruit increased at a lower natural mortality of 0.25 and 0.30 when the size of the lobster carapace length was increased (100- and 120-mm CL). It can also be observed that at a higher natural mortality (0.40 and 0.45) there was a decrease in yield per recruit of less than 60 gr per recruit at the same selection of carapace lengths.

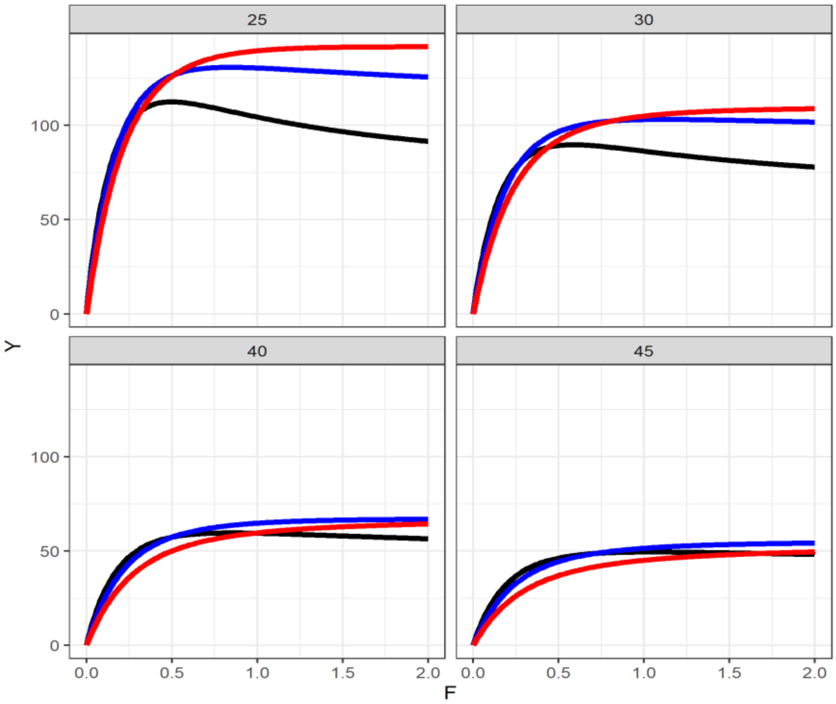

Figure 12 Yield Per Recruit (Y, in grams) vs. fishing mortality (F) at selected size at age by carapace length (black: 76 mm, blue: 100 mm, red: 120 mm).

5 DISCUSSION

This study assessed the current and historical stock health and sustainability of the Caribbean spiny lobster fishery in Belize. The results showed that Belize's lobster population is heavily exploited, resulting in fewer lobsters reaching a large size. Fishing mortality of two-year-old lobsters ranged from 0.5 to 1, with an average of 0.6 over the last five years. In this fishery, two-year-old lobsters are only partially selected. Fishing mortality was higher for 3- to 5-year-olds (2.6) but declined in 2016 and has gradually increased in recent years. Yield has increased since 2015 owing to increased recruitment and lower exploitation rates. Due to the inverse relationship between fishing mortality and biomass, it is necessary to control and/or reduce fishing effort to achieve sustainability of the lobster fishery by reviewing and reducing the number of licenced fishermen and fishing gear.

There was a substantial decrease in fishing mortality in 2017, possibly because of hurricane Earl. In 2016, the National Emergency Management Organization reported that the area impacted by Hurricane Earl accounted for an estimated 75% of Belize's annual lobster production. Based on damage assessments for the fisheries sector as a result of previous hurricanes that affected the northern part of Belize (Hurricane Richard and Hurricane Dean), fishing capacity took approximately five months to recover after hurricane disturbance. This loss of production is directly related to the loss of fishing capacity and recovery in affected areas (NEMO, 2016). Another destructive hurricane, Franklin, struck in August 2017. A potential avenue for future research is to quantify the impact of hurricanes on the fisheries sector.

Estimates of growth and maturity parameters were obtained from previous studies in Belize (Gongora, 2010). These parameters are similar to those obtained by Leon et al. (1995) for southwestern Cuba. The growth estimates for spiny lobsters in Cuba obtained by Leon et al. (1995) were accepted as the average for spiny lobsters in the Caribbean when reliable estimates were not available. The FAO (2001) report on the assessment of the Caribbean Spiny Lobster (*Panulirus argus*) considered the growth estimates reliable which were derived using the SLCA method and were used based on a large sample size collected during the 1990s, covering the widest range of size classes (Gongora, 2010; FAO, 2001). For this study, the proportion of maturity in each age group was obtained from Gongora (2010). These values were assumed to be fixed in time; however, further empirical studies should be conducted to improve our understanding of the variation in the spatial and temporal distributions of size at maturity within the spiny lobster stock in Belize. For fisheries management, it is important to determine how the proportion of mature biomass that is harvested is related to the minimum legal size and size at maturity because this will have important implications for egg production, larval settlement, and recruitment. According to Pollock (1993), the size at which sexual maturity is reached is an important population parameter that guides the establishment of minimum sizes for fisheries management.

Catch-at-age was estimated using the von Bertalanffy growth curve using age-length keys derived from size and age frequency data. The results of the slicing method were used as the baseline for the virtual population analysis. These results revealed that the youngest fished lobsters were two years old (4 ounces or 113.2 g). Given this knowledge, it is reasonable to believe that these young lobsters did not achieve their full size. The continued harvesting of small lobsters (4 ounces) is not a good fishing practice. To combat overfishing, the minimum lobster tail weight must be increased. Since 2006, several lobster producing nations such as Nicaragua and Honduras, have set a minimum lobster tail size of 5 ounces (141.7 g), with a lower restriction of 4.5 ounces (127.6 g) (OSPESCA 2006). The United States has approved laws requiring a minimum lobster tail weight of 5 ounces (141.7 g), with a lower limit of 4.2 ounces (119.1 g) and a maximum limit of 5.4 ounces (153.1 g) (Federal Register 2009). The minimum landing tail weight in Belize was recently increased from 4 to 4.5 ounces (Fisheries Amendment Regulation S.I No 128 of 2021), however given the assumptions used in this study, increasing the size limits to 10 ounces (100 mm CL) would increase the yield of the stock substantially. Such an increase could be implemented incrementally with further research and validation of the observed gain in each step. It can also be considered that larger, mature lobsters are normally located in deeper waters, while juveniles are more often found in mangrove areas, shallow seagrass beds, and coral reefs. As a result, overfishing of smaller-sized lobsters has occurred, particularly when there is little or no control over overfishing efforts, and the mortality of young recruits is high (Gongora, 2010). The mean fishing mortality rates for the study of older lobsters are higher, so there is a need to consider the reduction in fishing effort, and it is strongly advised to develop a research-based total allowable catch limit.

Mean carapace lengths (CL) and proportions by age for the lobster dataset collected using the slicing method (2-year-old lobster ranged from 71.02 to 76 mm and 3-year-old lobster ranged from to 84-104 mm). The similarity of these CL estimates leads to the conclusion that a 4-ounce lobster tail comes from a 2-year-old lobster, and a 6-ounce lobster tail comes from a 3-year-old lobster. Most of the lobsters landed in Belize are 2 to 3 years old. This study revealed that two-year-olds are only partially selected in this fishery. The estimated number of two-year-old recruits fluctuated around 2-2.5 million in 2015 and reached a maximum of 3.5 million in 2017. Subsequently, the number of 3- to 5-year-olds has increased in recent years.

The calculated CPUE values from individual trips were used as an index of lobster abundance and to tune the VPA estimates. Simple CPUE estimations based on the number of registered boats or fishermen include uncertainties. However, it should be noted that the number of fishermen and boats might not reflect the true fishing effort because the number of gears (traps) employed in the fishery is not quantified. It can also be noted that Belize does not have a species-specific fishing licence; hence, fishers engaging in fishing activities can target lobsters, conch, and finfish. Therefore, there is a need to determine the exact number of fishermen that only target lobsters and those that are opportunistic fishers.

For this assessment, a simple technique for tuning the virtual population analysis was applied. This assumed that catchability was constant in time and that effort was consistent across age classes, and additional information on catch-by-age and fishing effort, either from a fishery subcomponent or from a fishery-independent source such as a research survey, could be used to “tweak” the assessment to produce better estimates of fishing mortality and abundance in recent years. However, in this study, the model was limited by a lack of age-specific information on catch and effort that would have enabled deaggregated CPUE indices and thus facilitated a more rigorous assessment of the stock with VPA using extended Survival Analysis (XSA). Here, individual cohort sizes are used to estimate survivors at each age in the terminal population. Although the modelling approach is more involved, the method requires the same input of catch numbers and indices of catch per unit effort, and it retains the basic VPA method at its core. For future assessment, better data, such as CPUE by age indices, should be collected to assess the stock.

The assessment results are comparable to those of a previous study in 2010 (Gongora, 2010). Both studies showed that fishing mortality was high and that two-year-olds were heavily exploited, indicating the possibility of overfishing. A study in 2019 (Gutierrez, 2020) revealed similar results for smaller-sized lobsters at ages 2.5–3.5 years old. The fishing mortality from that study was 0.56, compared to the fishing mortality found in this study of 0.66 for 2-year-olds. It is possible that this decrease in fishing performance is not only attributable to fishing exploitation but also to changes in habitat conditions, water temperature, and extreme climatic circumstances (hurricanes), among others (Leon et al., 2007). However, this study revealed that the number of 3-to 5-year-old lobsters has increased since 2018. There is an increasing trend in the number of 2-year-old lobsters entering the fishery. This results in an increase in the total biomass and greater age diversity in the stock.

6 CONCLUSION AND RECOMMENDATION

In this study, an assessment of the Caribbean Spiny Lobster fishery in Belize was performed using the dataset of 1999-2021 and catch effort from 2000-2021. The virtual population analysis was tuned using the CPUE data. The results of this study indicate that the Belize lobster population is heavily exploited. Strong recruitment of two-year-old lobsters in 2015 and an even stronger cohort in 2017 resulted in an increased population size of 3-to 5-year-olds, and a corresponding reduction in excessively high fishing mortality. The two hurricanes that hit

Belize in August 2016 and 2017 are also likely to have facilitated the lowering of fishing pressure, with disturbance and short-term reduction in effort.

The results of this study suggest the following recommendations for fisheries managers in Belize:

1. Strengthen, standardise, and harmonise the monitoring and data collection of national efforts across stakeholders.
2. There is a need to implement a lobster recruitment study program to estimate juvenile abundance index. For instance, more lobster sampling (frequency and location) is necessary to obtain improved estimates of population growth parameters. Additionally, a deep-water lobster stock assessment should be conducted.
3. Monitor and assess illegal fishing and unreported catch in the domestic market and increase communication and collaboration among co-managers. Reduce fishing effort by limiting the number of fishers and gear employed in the fishery.
4. The minimum lobster tail weight of 4 ounces (113.4 g) should be increased to 4.5 ounces (127.6 g) and preferably to even larger sizes.
5. An estimated Total Allowable Catch for quota distribution would assist in sustainable management of the fishery.

ACKNOWLEDGEMENTS

First, I would like to thank the Almighty for giving me the strength and guidance to push through with this very intense training. The GRÓ FTP team under the auspices of UNESCO provided me with the opportunity to participate in this training course. Special thanks to the head of the ARAM line Dr. Jónas P. Jónasson who gave his constant support to the entire Aquatic Resource Assessment and Monitoring group.

I would also like to express my special thanks to my mentors, Dr. Jónas P. Jónasson and Dr. Will Butler for their time and efforts provided throughout these six months; your useful advice and suggestions were helpful to me during the project's completion. In this respect I am evermore grateful to you both. I also extend my huge thanks to Mr. Rigoberto Quintana, Ag. Fisheries Administrator for his support on this training. In addition, my colleagues provided kind assistance in every way.

Finally, I thank my FTP fellow colleagues who originate from a diverse array of cultures from various countries for their kind friendship and for sharing so many memorable occasions during our time of study.

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8 APPENDIX

Year	4 OZ	5 OZ	6 OZ	7 OZ	8 OZ	9 OZ	10-12 oz	12-14 oz	14-16 oz	16-20 oz	20-24oz	24oz & up	Total (t)	Total Production (t)
1999	58.0	40.3	29.3	20.4	15.1	11.2	16.5	7.6	3.6	2.5	0.6	0.0	**205.1**	**276**
2000	38.8	38.7	34.2	27.9	22.2	18.1	28.4	12.8	6.0	5.1	1.6	0.0	**233.9**	**252**
2001	29.4	29.3	25.6	20.8	18.2	14.6	24.4	11.3	6.0	4.9	1.5	0.0	**186.0**	**196**
2002	40.8	37.9	33.2	26.7	22.2	16.6	25.4	11.6	5.6	4.6	1.6	0.0	**226.2**	**267**
2003	39.9	39.4	28.7	25.9	20.1	14.4	23.1	10.6	5.1	4.3	1.4	0.0	**212.9**	**248**
2004	41.5	44.2	38.8	31.3	23.8	17.4	22.9	11.6	4.9	4.3	1.7	0.0	**242.4**	**254**
2005	32.1	39.8	33.7	28.4	22.8	16.8	23.8	12.4	4.8	4.2	1.3	0.0	**220.0**	**223**
2006	25.3	34.0	28.5	22.6	18.0	13.5	20.4	9.3	4.5	3.9	1.0	0.0	**181.0**	**190**
2007	21.5	29.2	25.2	22.8	18.4	14.2	20.5	7.3	3.7	3.4	0.8	0.0	**167.0**	**210**
2008	19.4	37.9	30.2	25.0	19.8	13.9	20.2	8.3	4.1	4.3	1.0	0.0	**184.1**	**213**
2009	19.2	50.2	35.9	29.1	22.4	17.0	27.6	9.5	4.8	4.2	1.2	0.0	**221.1**	**211**
2010	19.5	40.3	33.0	25.7	19.8	14.6	23.9	9.3	4.6	3.9	0.8	0.0	**195.4**	**227**
2011	19.6	47.7	37.3	31.1	24.3	19.5	28.1	10.6	4.9	4.1	1.0	0.0	**228.5**	**277**
2012	6.5	42.1	31.0	28.2	24.0	17.9	26.8	9.3	4.7	4.1	1.0	0.1	**195.7**	**224**
2013	19.3	53.6	33.0	25.1	19.4	14.6	21.7	8.9	4.6	4.6	1.2	0.1	**205.9**	**225**
2014	8.1	60.4	33.0	25.6	19.8	14.4	21.1	8.0	3.9	3.6	0.9	0.1	**199.0**	**220**
2015	15.9	68.7	46.5	31.5	23.2	16.5	19.5	7.0	3.0	2.6	0.7	0.1	**235.3**	**289**
2016	17.3	59.3	45.1	29.3	22.7	18.1	22.7	9.7	10.3	2.8	0.7	0.3	**238.3**	**264**
2017	17.8	21.0	8.8	6.0	3.9	2.8	2.9	1.2	0.6	0.4	0.1	0.0	**65.6**	**321**
2018	13.2	61.6	45.2	34.2	26.3	22.0	21.9	18.0	7.9	4.8	2.1	3.0	**260.2**	**275**
2019	36.5	52.9	50.0	39.6	31.8	23.0	23.3	30.3	15.7	12.6	4.1	5.6	**325.4**	**327**
2020	39.5	55.4	52.6	46.7	36.7	27.0	26.5	34.7	15.0	9.3	5.1	1.1	**349.6**	**336**
2021	0	52	43	42	38	18	25	14	11	4	2	5	**253.0**	**357**

Table A 1 Lobster tails by size categories from the cooperatives in Belize for the period 1999-2021.

Catch at age in '000s of individuals (the CL frequencies using Slicing Method of Sparre and Venema (1998) linf=183,k=0.24 to=0.44

Ages	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
2	1271073	848071	628380	936584	902972	916890	744366	638961	656321	685130	672345	724379
3	426741	510395	402851	527060	478456	499773	461824	386625	458053	448422	443823	477853
4	19702	29463	28057	29416	26772	24171	22372	21394	21329	23397	21069	23546
5	443	1018	950	1093	957	1046	741	621	585	675	667	566
Ages	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	
2	847334	584491	781315	770694	1227652	883241	1711713	824920	952246	967405	1094971	
3	606607	530023	434049	459834	643936	512187	386448	572093	644413	712574	760461	
4	26416	24088	24101	21023	19216	34749	12183	33441	69938	59913	44390	
5	713	855	898	831	658	1041	415	5987	10701	4399	10865	

Table A 2 Catches at age in '000s of individuals using growth parameters from Gongora (2010)

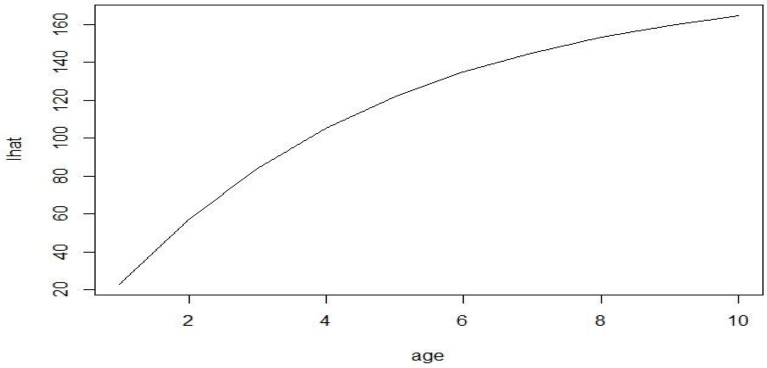

Figure A 1 Catch at age growth curve at the crrent landing carapace lengths. Used the growth parameters of Gongora (2010= with raised number of individuals for catches by year: L∞ = 183mm, k = 0.24, and t0 = 0.44

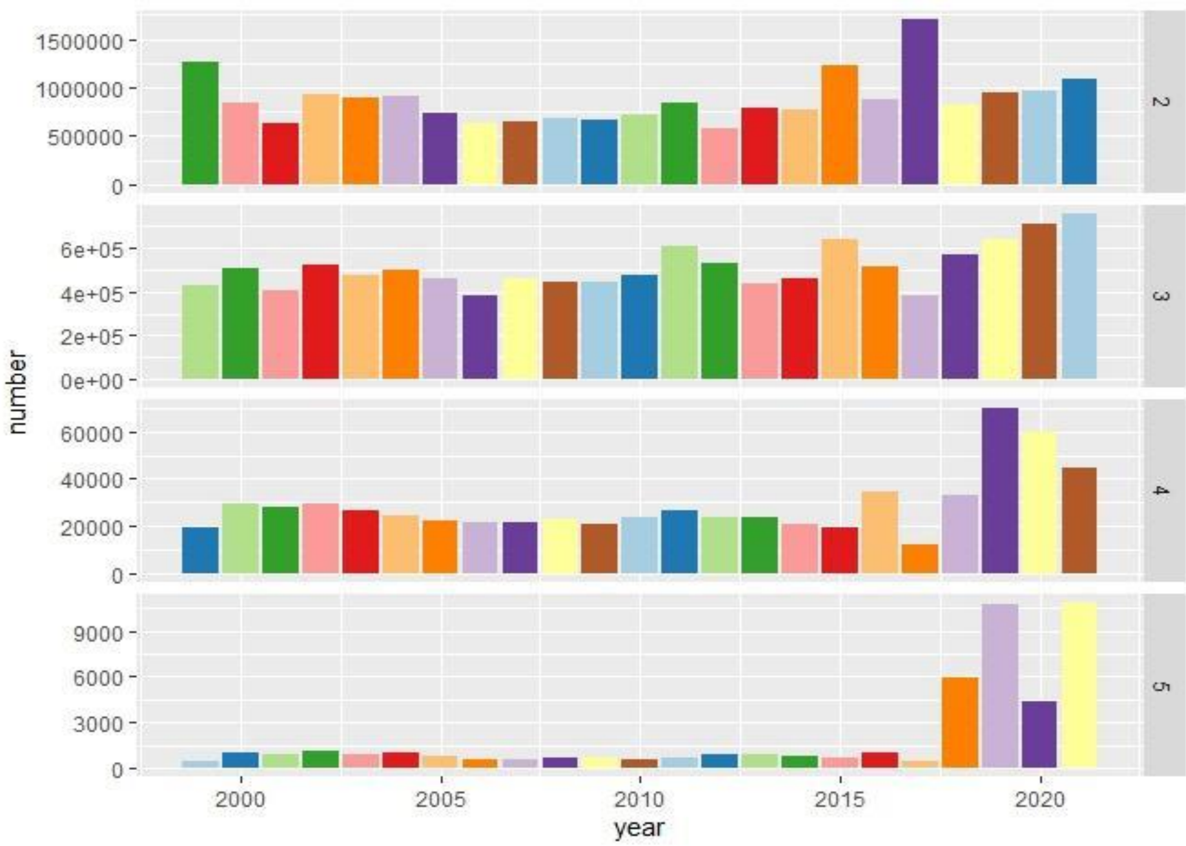

Figure A 2 Raised number of individuals by carapace lengths using the slicing method.

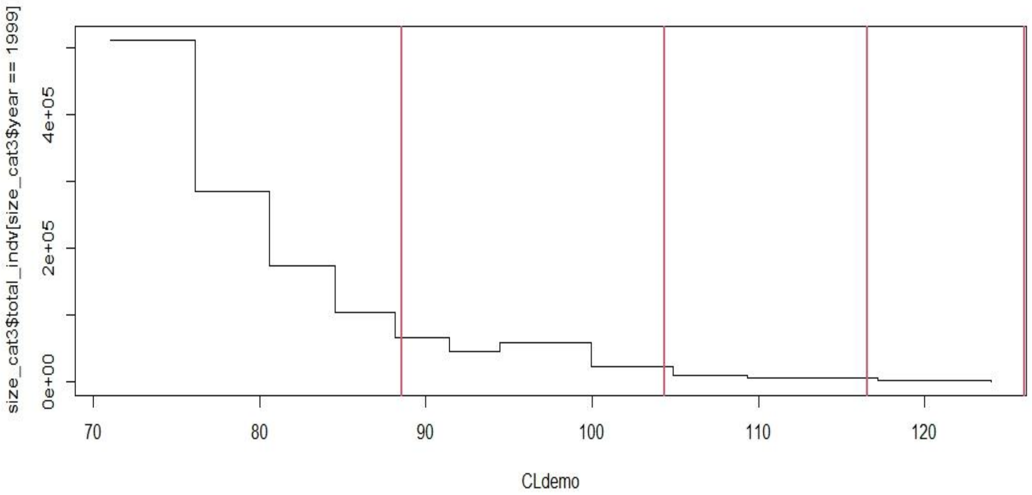

Figure A 3 Illustration of the trend by number of individuals by age for the years using the growth parameter (Gongora, 2010). Assumed growth with raised number of individuals for catches by year: L∞ = 157.67, k = 0.26, and t0 = 0.829.

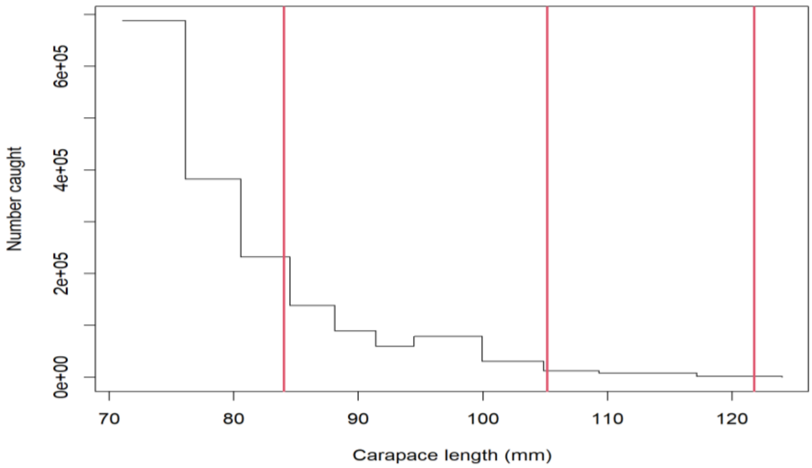

Figure A 4 Raised number of individuals by Carapace Lengths using the slicing method (Catches ages 3-6yrs). Assumed growth with raised number of individuals for catches by year: L∞ = 157.67, k = 0.26, and t0 = 0.829.

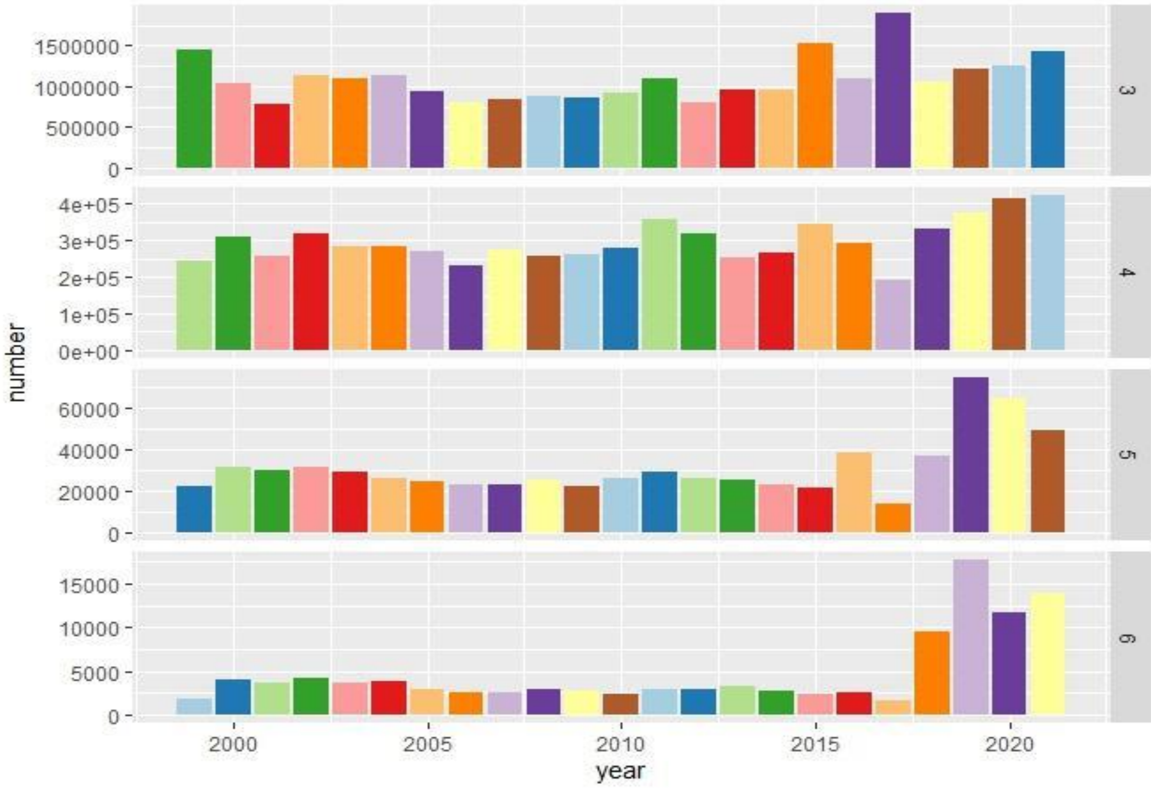

Figure A 5Trend of raised number of individuals by age (3-6) for the years 1999-2021.

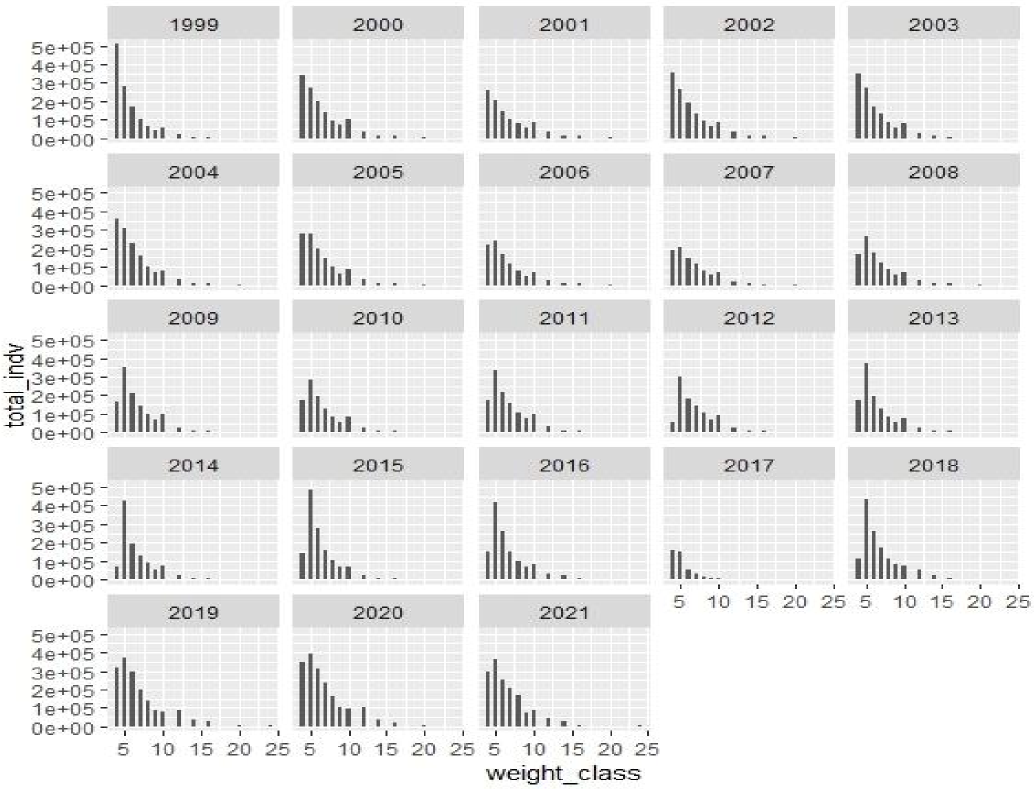

Figure A 6 Total number of individuals by weight class (4-24 oz) for the period 1999-2021.

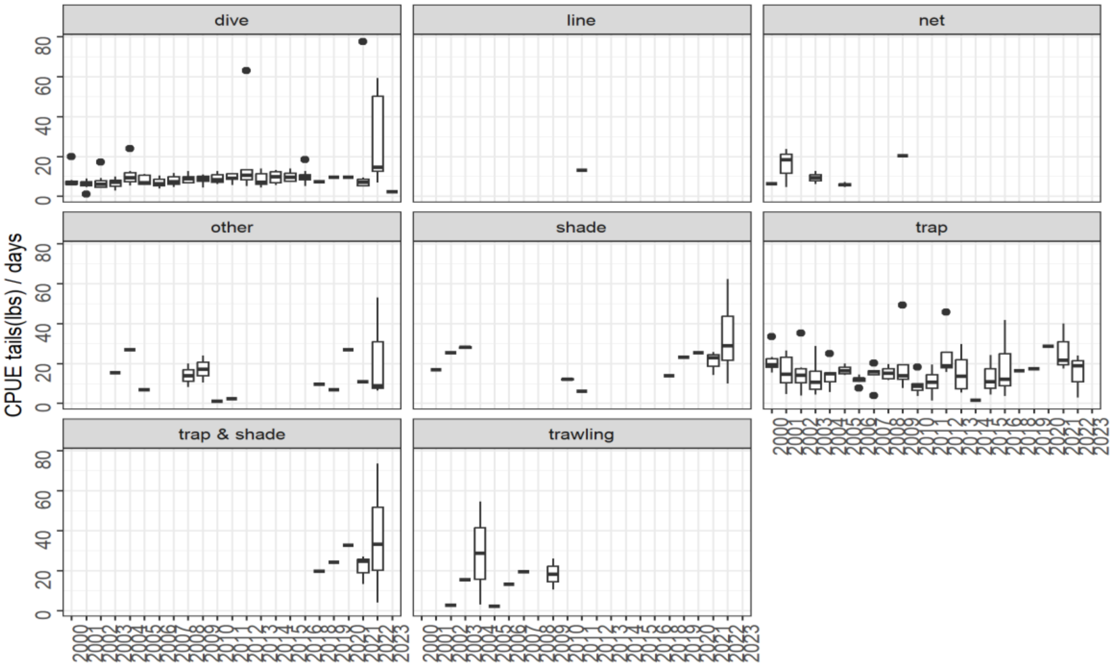

Figure A 7 CPUE by different gears for the time-series 2000-2021 data set.

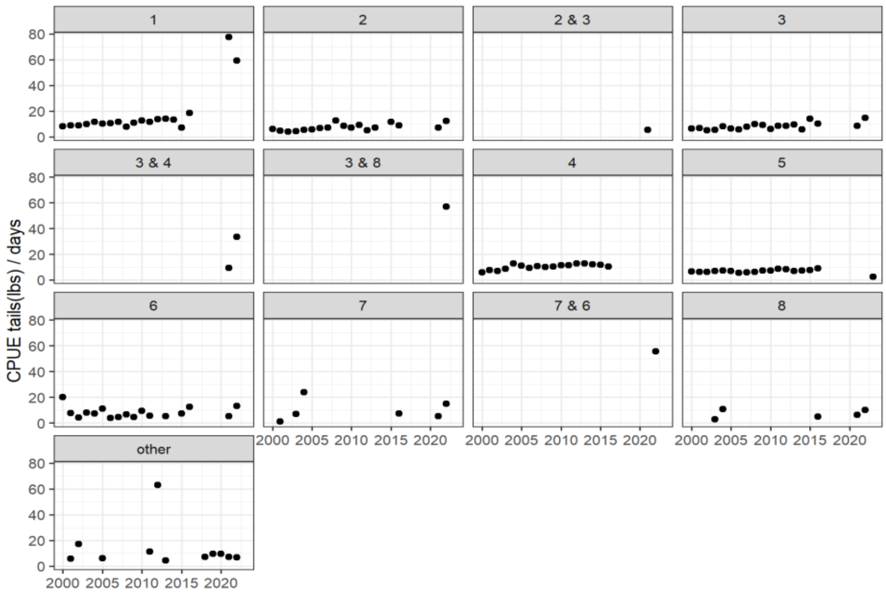

Figure A 8 CPUE by different areas for the time-series data set (2000-2022).

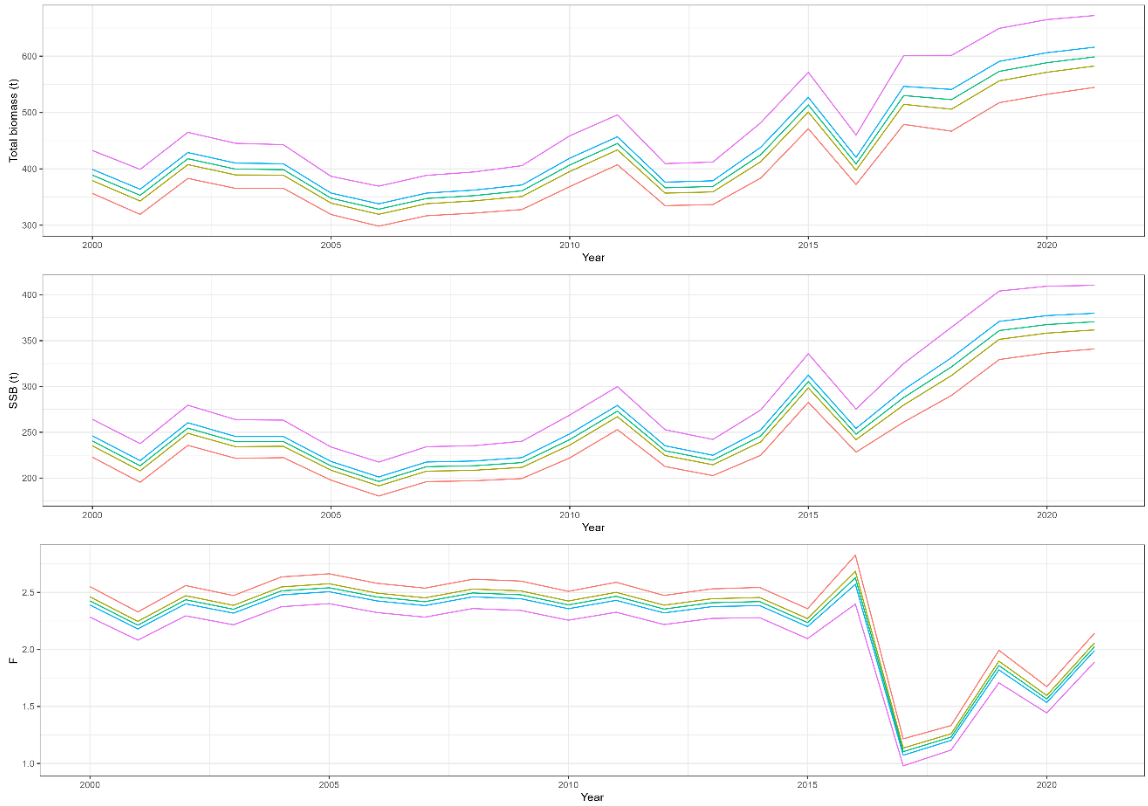

Figure A 9 Sensitivity analysis showing different assumed natural mortality against biomass, fishing mortality and SSB (t) (1999-2022).