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Environment and Natural Resources

The Application of a Bioeconomic Model to Analyse the Jamaican Industrial Spiny Lobster (*Panulirus argus*) Fishery

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Faculty of Economics

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HÁSKÓLI ÍSLANDS

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60 ECTS thesis submitted in partial fulfillment of a *Magister Scientiarum* degree in Environment and Natural Resource

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Abstract

The Jamaican industrial spiny lobster fishery is one of Jamaica's most valuable fisheries, second only to queen conch. Irrespective of this, the fishery has had zero fishery-independent surveys of its stock to ascertain a biomass estimate, resulting in the spiny lobster fishery not having an established Total Allowable Catch (TAC). This project aims to determine if Jamaica's industrial spiny lobster fishery landings are sustainable by calculating a maximum sustainable yield (MSY), maximum economic yield (MEY), and finally, determine the ideal measure of effort to be utilised in its management. A bio-economic model was developed using an estimate of biomass from a fishery-independent survey. This biomass estimate was employed to calibrate the Schaeffer production model, which yielded growth parameters that were applicable within six (6) years of landing data (2015 to 2021) to determine the spiny lobster fishery reference points. The number of trap days was the best measure of effort for managing the spiny lobster fishery, of which the fishery reference points are MSY of 323 mt, a MEY of 314 mt at a maximum of 1400 traps and thirteen (13) days per trip. However, Jamaica's annual spiny lobster fishery landings average 301 mt over the last six (6) years. Though the fishery does not appear to be overfished, illegal, unreported and unregulated (IUU) fishing is a significant and unaccounted for issue. Therefore, it is advised that Jamaica's fisheries regulatory body implement a TAC set at 314 mt through an individual quota (IQ) system to safeguard the long-term sustainability and profitability of the fishery.

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1 Introduction

1.1 Rationale and objectives

The Jamaican spiny lobster fishery was last analysed by Morris (2010) using the 1997-2007 industrial spiny lobster fishery data set. He deduced that the fishery was overcapitalised and that a rights-based system would be the best option for its management. Morris (2010) utilised a bioeconomic model to analyse the industrial spiny lobster fishery. Unfortunately, the government of Jamaica has taken no measures to address the findings of this study.

Historically, the spiny lobster fishery has been one of Jamaica's top-producing fisheries, second only to the queen conch with annual exports of around 190 mt. Its importance was further elevated recently due to the closure of the queen conch fishery in 2019. As a result of this closure, the industrial fishers relied upon the fishery more heavily for income. It then became a priority for the authorities to better understand the fishery's bioeconomic indicators, including biomass, catch, and profits with respect to levels of effort. This resulted in the conducting of a three-year spiny lobster abundance survey initiated in 2020 on Jamaica's main fishing ground, the Pedro Bank. This study will build on previous fishery-dependent assessments using fishery-dependent data from 2015 to 2021 and incorporate a fishery-independent analysis from the 2020 survey. The sum of this analysis is aimed at answering the following research questions:

i. What are the maximum sustainable yield (MSY) and maximum economic yield (MEY) of the Jamaican industrial spiny lobster fishery?
ii. What is the best policy decision for ensuring its sustainability and profitability?

The objectives:

1. To develop a bioeconomic model to answer the above research questions.
2. To develop management recommendations for the Jamaican industrial spiny lobster fishery.

1.2 Biology and life cycle of spiny lobster

The Caribbean spiny lobster, *Panulirus argus*, occurs in tropical and subtropical environments and has a five-stage life cycle: adult, egg, larva (phyllosoma), puerulus, and juvenile (Figure 1).

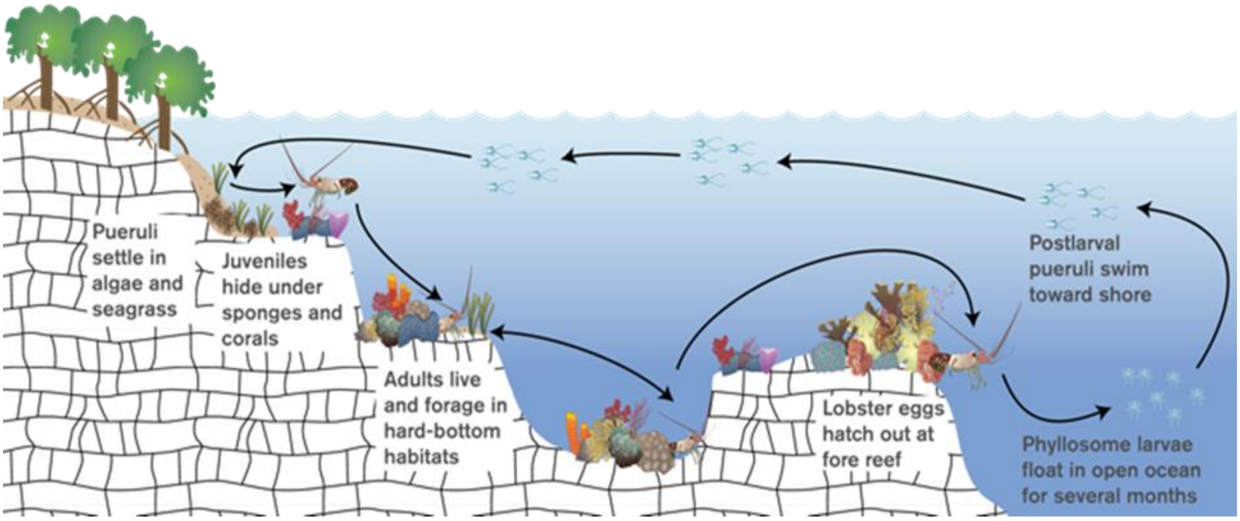

Figure 1: The Spiny Lobster's Life Cycle. (Leahy, 2010)

The post-larval and early juvenile stages live in shallow waters, preferring protected areas such as coastal margins, mangrove and seagrass beds (Chakalall & Cochrane, 2007). Adults can be found at depths of at least 100 meters in rocky environments and coral reefs (Munro, 1974). Spiny lobsters are distinguished by their rounded head (carapace), forward-facing spines, large rostral horns, and lengthy spiny antennae. Young juveniles exhibit a broad range of body colours, ranging from brown, purple, and black; however, in adults, colours range from brown, light grey, and red (Marx & Herrnkind, 1985).

Spiny lobsters display sexual dimorphism, with males having more extensive and heavier carapaces and females having lighter and shorter tails (Munro, 1974). Growth in the first year is approximately 5 cm each year, although it can reduce significantly to an average of 2.5 cm (Martin-Murray, 2009). Temperature and population density in the local environmental impact growth and moulting, and younger individuals are more likely to experience them (Marx and Herrnkind, 1985).

Females achieve sexual maturity at 7.8 to 8.3 cm carapace length; during mating, males deposits a waxy spermatophoric mass on the female's sternum (Marx and Herrnkind, 1985). Later, females transfer the eggs across the spermatophore, allowing fertilisation to occur (Marx and Herrnkind 1985). Females move to deeper waters to spawn after approximately four weeks of fertilisation and incubation (Munro 1974). Spawning occurs mainly between February and August, but some spawning occurs throughout the year (Marx and Herrnkind, 1985; Munro, 1974), typically temperatures around 24ºC (Lyons 1980). The number of eggs that a female can carry ranges between 2000 to 2500 (Fonseca-Larios & Briones-Fourzan, 1998).

Planktonic larvae develop in the Caribbean for 6 to 10 months (Alfonso et al., 1991). The larva (XI stage) will migrate towards the coast in 4 to 8 days after metamorphosis to the puerulus stage, where its carapace length (CL) is 0.56 cm (Butler & Herrnkind, 1991). Maximum settlement periods are August to December (Cuba, Mexico Caribbean, Jamaica, Antigua, Costa Rica and Bermuda) and February to March (Florida Keys). The puerulus settle on surfaces coated in red macroalgae clones, *Laurencia spp* (Marx & Herrnkind, 1985). The puerulus metamorphoses into the post puerulus stage or algal phase after settlement, with sizes ranging from 0.61 to 1.65 cm CL (between 2 and 5 months). Between 8 and 11 days after settlement, the post puerulus transforms into the juvenile stage. At about 2.0 – 2.8 years of age, juveniles are recruited into fisheries between 7.6 and 7.7 cm CL (Butler & Herrnkind, 1997).

Because of the species' vast range, great fecundity, and year-round reproductive activity, a continual supply of larvae is disseminated across the region (see Table 1). The largest larval populations have been documented south of Cuba, in the Yucatan Strait's entrance, east of Belize, north of Honduras, north of Venezuela, in the Florida Straits, and in the Bahamas' Viejo Canal (Alfonso et al., 1991).

Table 1: Time intervals of spiny lobster pueruli settlement over the Caribbean Region (Meggs et al., 2010)

Location	**Peak months of settlement**	**Reference**
Australia	September to January	Phillips 1986
Antigua	February, May September to October & December	Bannerot *et al.* 1987b
Puerto Rico	June – August	Bannerot,1987b
Cuba	May to July & September to November	Cruz *et al.* 1992a
Florida	February to May	Menzies & Kerrigan 1980
Mexico	March to April & September to October	Gutierrez *et al.* 1989
Bahamas	September, November, and February	Afonso & Gruber, 2007
Jamaica	July & October to November	Young, 1993 and Meggs *et al.* 2010

1.3 Study site

Jamaica is one of the three major Caribbean islands, Greater Antilles (Figure 2), with a land area of 10,991 km^2, located 145 km south of Cuba and 161 km west of Haiti. Jamaica has an estimated maritime space that is 25 times the size of the main island. Jamaica's coastline is made mainly of mangroves, seagrass beds, and coral reefs, which account for 90 per cent of marine fisheries but less than 15 per cent of maritime area (Cooke-Panton, 2014).

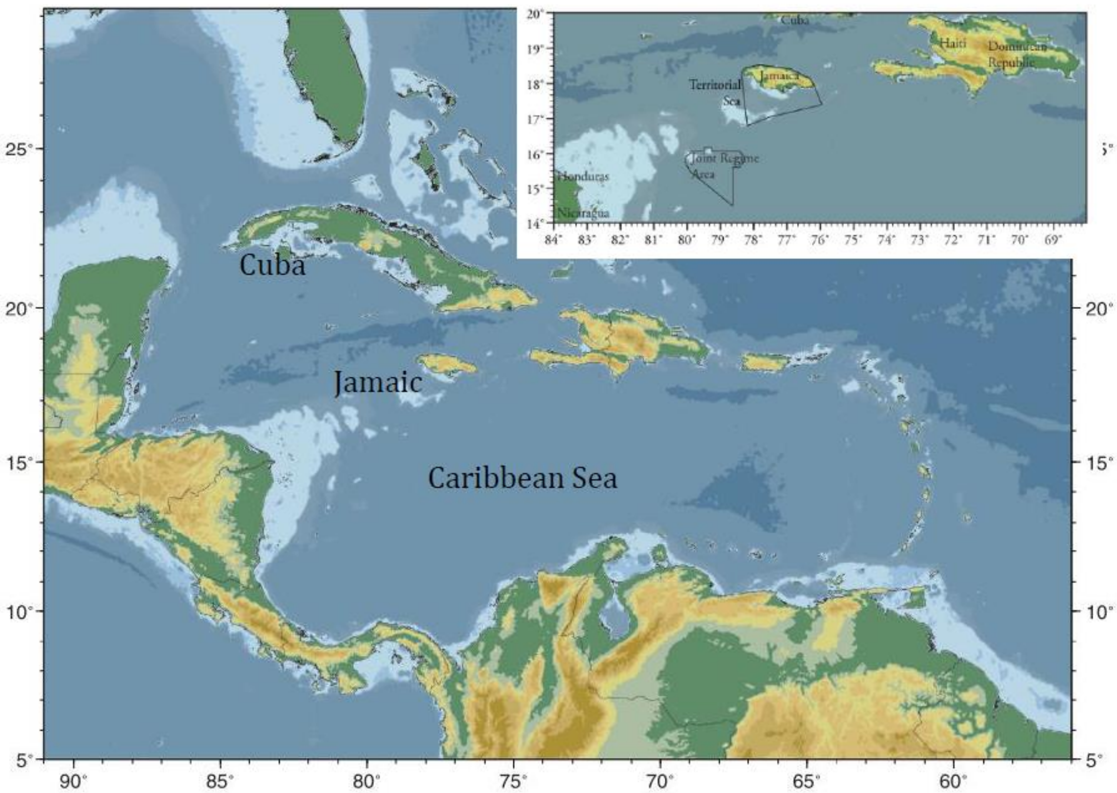

Figure 2: Jamaica's location within the Caribbean. source: CFRAMP (2000, as cited in Hutchinson & Girvan, 2021)

The Jamaican spiny lobster fishery is located in the Caribbean Sea, with fishing taking place to the south of the island on banks such as Pedro Bank, Morant Bank, and Formigas Bank (Haughton & King, 1992) (Figure 3). On the other hand, Pedro Bank is a significant fishing ground that accounts for roughly 60% of all landings in the industrial fishery (Fisheries Division pers. comm. 2021). The industrial fleet concentrates its fishing effort between the 20 m and 40 m depth (Figure 4). For this study, the depth zones of interest are 10 m, 20 m, and greater than 20 m.

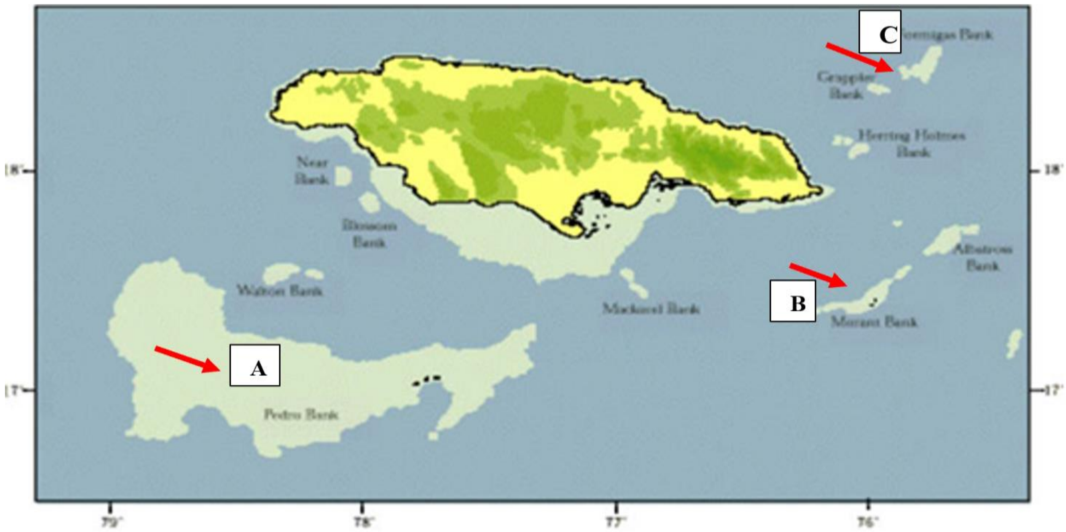

Figure 3: Important spiny lobster fishing grounds in Jamaica; A - Pedro Bank, B -Morant Bank, C - Formigas Bank; (Cooke-Panton, 2014)

Figure 4: Depth zones located on the Pedro Bank. white polygon = 10 m, pink line = 20 m, yellow line = 30 m and red line = 40 m depth contour. (NFA, 2021; Google, 2015)

1.4 Importance of the spiny lobster fishery

The spiny lobster stock supports the region's most economically important fisheries (Ehrhardt et al., 2011), engaging more than 32,000 fishers in 25 countries (Chavez, 2007). Open-access and unregulated management systems are standard within the region, except in Florida, Mexico, Cuba, and Belize (Chakalall & Cochrane, 2007; Ehrhardt et al., 2009; WECAFC, 2007), where frequent stock assessments are conducted and catch controls are utilised.

Overcapitalisation and overexploitation are conditions that affect both managed and unmanaged fisheries (Chakalall, & Cochrane, 2007; WECAFC, 2007). Biological controls which govern the Jamaican spiny lobster fishery include size limits, reproductive stage limits, gear limits, vessel limits, and seasonal closures (Cooke-Panton, 2014). Total Allowable Catch (TAC) is not being utilised in this fishery, which could aid in harvest and economic control (Cooke-Panton, 2014); instead, the focus is on biological controls. Studies on spiny lobster management have shown that using only biological controls as management measures will not guarantee a sustainable fishery (Knútsson et al., 2016). A combination of biological and economic measures are necessary to improve the fishery's sustainability and profitability (Knútsson et al., 2016). Therefore, incorporating harvest controls to the Jamaican fishery, such as individual quotas, could advance the fishery towards being more efficient and sustainably (Hannesson, 1993).

In Jamaica, the spiny lobster fishery became Jamaica's top fishery in 2018, with exports totalling 192 mt (US$5 m) (STATIN, 2018), mainly due to a moratorium on the queen conch fishery due to a significant stock decline. To avoid such a scenario for lobster, a bioeconomic assessment to determine stock levels and sustainable yields is a priority. The development of rights-based management has been stymied by a paucity of economic data and absent or unreliable fishery parameters estimations, resulting in a limited number of assessments of the fisheries (Morris, 2010). The lack of rights-based management has been shown to lead to overexploitation and overcapitalisation in a "race to fish" scenario (Arnason, 1993). A management system geared towards property rights management will help to avoid these pitfalls and move the attention of fishers from quantity to profitability.

1.5 Spiny lobster fishery management in Jamaica

1.5.1 Policy and governance

The National Fisheries Authority (NFA) is the primary fisheries management body that oversees the fisheries sector, conducts research, and implements fisheries policy. The agency collaborates with various stakeholders, including the national security and enforcement bodies, environmental agencies and non-government organisations, to manage the sector (Morris, 2010). Additionally, the NFA maintains a licence and registration system, vessel and catch monitoring, biological monitoring, and supports species-specific research. Management challenges include illegal, unreported, and unregulated fishing by both non-locals and locals, and the aforementioned overcapitalisation (Morris, 2010).

The Fisheries Act of 2018 governs the spiny lobster fishery (formerly The Fishing Industry Act of 1975). This Act instituted increased fines by several-fold compared with the previous Act for fisheries breaches resulting in potential fines of over US$20,000 (FAO, 2021). A summary of the Act's main instruments as it relates to lobster include (Fisheries Division, 2019a):

1. The minimum legal size of carapace length (CL) 7.6 cm.
2. Egg bearing female lobsters are protected.
3. The annual closed season for the period April 1 – June 30.
4. Effort restrictions include limited entry of 17 vessels and gear restrictions of 2200 trap limit.

There was no established process for spiny lobster licensing in Jamaica before 2017. This was developed and instituted in 2017 to formalise the industrial lobster licensing procedure. A specific licence under this regime has a lifespan of two years and costs approximately US$850 (FAO, 2021).

The management measures described in the 2018 Act cover both the artisanal and industrial fleets; however, the licensing regime only addresses the industrial fleet (National Fisheries Authority, 2020a). Other stipulations include landing catches no later than ten (10) weeks following the beginning of each fishing expedition.

1.5.2 Spiny lobster fleet description

The industrial lobster fleet consists of steel-hulled vessels, of mean total length of 19 m with a range of 8 - 29 m (Figure 5), with inboard engines of approximately 500 hp (Kelly, 2002). Crew size range between 3 - 25 persons, with a mean of 11 persons. There are two categories of industrial vessels, carrier and fishing. The carriers transport the product from a fishing vessel to a port. They make short (one day) trips to the fishing grounds, whereas fishing vessels can spend 70 days at sea. The main fishing ground is Pedro Bank, where Florida wooden traps are the main fishing gear used (Figure 6). The total catch of the industrial fleet has averaged 301 mt over the last six years (Figure 7) at an average of 84 trips per year for the period. Landings are highest in March when the season ends and when the season opens in September. Landings are processed as frozen whole lobster and tails or as live lobster, with live lobster being the most valuable product. The industrial lobster sub-sector employs about 400 people, including fishers and those involved in processing (National Fisheries Authority, 2021).

Figure 5: Industrial fishing vessel 23 m in length

Figure 6: Florida wooden trap used by Jamaican industrial lobster fleet.

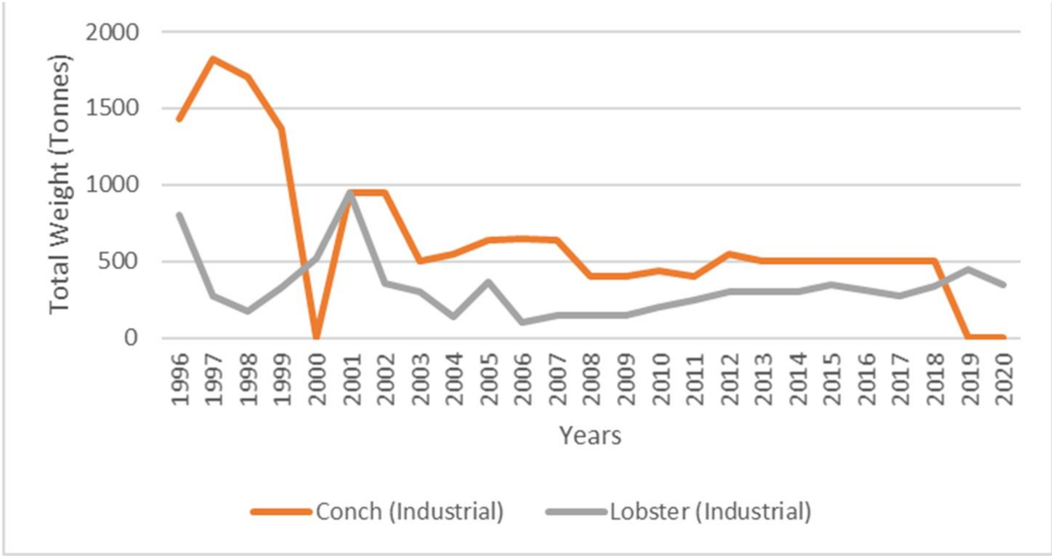

Figure 7: Jamaica’s Industrial fleet seafood production 1996 to 2020.

The artisanal lobster fleet utilises both motorised and non-motorised vessels (40-60 hp) with a three-person crew (Kelly, 2002). Artisanal fishers fish from the mainland and a small portion, mostly divers, from the Pedro Bank. Methods used to fish for lobsters are diving and the Antillean z-traps (Morris, 2010). These fishers sell to primarily local markets, including households, hotels, and restaurants (Martin-Murray, 2009). Artisanal lobster landings are not exported due to their inability to maintain the quality of the landed product. Though the artisanal sector employs almost 3300 persons, the lobster catch is only a target for a few and is a bycatch for most (National Fisheries Authority, 2021).

1.5.3 Studies on Jamaican spiny lobster

Most studies have focused on fishery-dependent data. Gittens (2001) for instance, demonstrated a decrease in the mean size of lobsters caught in Jamaica and the profusion of lobster on the south island shelf and the Pedro Bank. According to his study, approximately 30% of lobsters landed from the Pedro Bank were less than 50% mature, indicating likely recruitment overfishing and low biomass levels. Studies such as Aiken (1983) and Kelly (2002) reported that catches of undersized-sized lobsters also hampered the fishery. In 1975, the Fisheries Division, now the NFA, reported that 75% of the lobsters landed were immature females and recommended stricter management measures (Kelly, 2002). Later CRFM (2009) reported that 30% of the total lobsters sampled from the artisanal and industrial fleets were below minimum legal size (7.6 cm carapace length), representing a slight improvement.

Other studies have looked at the closed season's effectiveness to determine if the current three months (April to June) closure should be altered. Such studies include CRFM (2007) using 1996 to 2006 data to develop a recruitment index using catch and effort data for the southern shelf and Pedro Bank. This study found that recruitment might be occurring in August, roughly one month after the closed season, but inconclusive results. Another study reported that recruitment might occur between February and June, and to a lesser extent, between August and September (Cooke-Panton, 2014). As a result, the closed season was suggested to be gradually moved from April to February or designated closed areas during the recruitment period (Cooke-Panton, 2014). CRFM (2007) indicated that fishing methods, such as hookah negatively affected stock recruitment. Also, the variation of carapace lengths was lowest in March and August and highest in September and November, and the necessity for monitoring and the collection of economic data on the lobster fishery.

1.5.4 Stock assessment methods used to assess the spiny lobster

Since introducing an industrial lobster fleet in the 1980s (Haughton & Shaul, 1989), Jamaica has had various studies on the spiny lobster's growth parameters and stock size. Haughton & Shaul (1989) used ELEFAN 1 (Brey & Pauly, 1986) to estimate the growth coefficient (K) and asymptotic length (L_{oo}) of the von Bertalanffy growth functions but found that estimates were higher than those found in neighbouring countries. Using a larger sample size, Haughton & King (1992) tried to re-estimate the spiny lobster growth parameters using ELEFAN 1 (Brey & Pauly, 1986) coupled with a modal progression analysis (LFSA – length composition based fish stock assessment computer programs) (Jones, 1984; Sparre, 1987). This study found mean carapace lengths for males and females at 10.1 cm and 9.3 cm, with a mean of 9.7 cm. The recruitment size was estimated at 10.7 cm for males and 10.0 cm for females, larger than the established CL of 7.6 cm. ELEFAN 1 results for K is 0.24/year for males and 0.28/year for females, whereas the L_{oo} value for males is 21 cm and 19.5 cm. Mortality was estimated at 0.59 for males and 0.67 for females. This study also utilised Jones's Length Converted Cohort Analysis (Jones, 1984) to estimate biomass at approximately 4000 t.

Studies focused on calculating maximum sustainable yields (MSY) used statistical approaches such as Bayesian statistical analysis (CRFM, 2009) with MSY of 200 mt. The Schaefer surplus production model (MSY = 222 mt), Virtual Population Analysis

(VPA) – Jones' length-based cohort analysis and Thompson Bell Prediction Model (MSY = 205 mt) used by Martin-Murray (2009). Morris (2010) used a bio-economic model with a Schaefer surplus production model to carry out his assessment, resulting in an MSY of 222 mt and a MEY of 170 mt.

2 Methods and materials

2.1 Fisheries and bioeconomic model

The Gordon-Schaefer surplus production model has been used to assess the Jamaican spiny lobster fishery (Morris, 2010). This model is the most suitable for studying spiny lobster given the data limitations, though it may not be biologically realistic (Larkin et al., 2002). For this study, a fisheries bioeconomic model similar to the one described in the Sunken Billions Revisited (World Bank, 2017) is used to analyse the Jamaican spiny lobster fishery.

2.2 General model

The functional components for modeling the Jamaican industrial spiny lobster fishery included:

1. Net biomass growth function

   $$\dot{x} = G(x) - y \tag{I}$$

   where $G(x)$ is biomass growth as a function of biomass, y is harvest and $\dot{x} \equiv \frac{\partial x}{\partial t}$ represents the instantaneous change in biomass.

2. Harvesting function

   $$y = Y(e, x) \tag{II}$$

   where harvest, y, is a function of fishing effort, e, and biomass, x.

3. Profit function

   $$\pi = p \cdot Y(e, x) - C(y, e) - fk \tag{III}$$

   where P is the price of the catch; fk is fixed cost; $p \cdot Y(e, x)$ denotes the fishing revenues, $C(y, e)$ is the harvesting costs linked to fishing effort and harvest because the crew is given a share in the landed catch value as a bonus, apart from their fixed salary.

2.3 Model specifications

The biomass growth function for the Jamaican spiny lobster utilised the Schaefer surplus production model as specified below.

$$G_t = \rho x_t \left(1 - \frac{x_t}{K}\right) \tag{IV}$$

where x_t is the stock size at time t, G_t is growth at time t, ρ is the growth rate and K carrying capacity.

A modified Schaefer harvesting function is specified below:

$$q_t = \theta e_t x_t \tag{V}$$

where q_t is catch/harvest at time t, θ is catchability, and e_t is a fishing effort at time t.

The net benefits (profits) function:

$$\pi = pq - ce \tag{VII}$$

where p is the price of the catch, q is the cost associated with a unit of effort, c is the cost per unit of effort and e is the effort.

2.4 Spiny lobster fishery reference points

2.4.1 Static reference points

The reference points maximum sustainable yield (MSY) and maximum economic yield (MEY) were estimated from the model described above. Biological reference points for the fishery were estimated as follows:

$$q = \theta e x$$

$$G = \rho x \left(1 - \frac{x}{K}\right)$$

when q=G we obtain:

$$x = K\left(1 - \frac{\theta e}{\rho}\right) \tag{VIII}$$

We then inserted the equilibrium function into the harvest function and get:

$$\frac{q}{\theta e} = K\left(1 - \frac{\theta e}{\rho}\right)$$

$$q = K\theta e - \frac{K\theta^2}{\rho} e^2$$

Which can be expressed as:

$$q = \alpha e + \beta e^2 \tag{IX}$$

Or

$$CPUE\ (\frac{q}{e}) = \alpha + \beta e$$

To find effort that gives MSY we maximise equation (IX) to get:

$$e_{MSY} = -\frac{\alpha}{2\beta} \tag{X}$$

The harvest function then equates to:

$$h_{MSY} = -\frac{\alpha^2}{4\beta} \tag{XI}$$

The profit-maximising MEY biomass (X_{MEY}) fixed reference point is attained by maximising the profit function (VII) to give:

$$\pi(e) = P(\alpha e + \beta e^2) - ce$$

Which can be expressed simply as:

$$\pi(e) = P(\alpha e + \beta e^2) - ce \tag{XII}$$

Cost can then be calculated as:

$$Cost = ce + 0.25pq$$

where the cost (c) of a unit of effort (e) plus the percentage of wages (25%) of the price (p) of the total catch (q). The total cost can then be expressed as:

$$cost = \frac{Total\ Cost}{effort}$$

2.5 Data sources

2.5.1 Survey data

The NFA carried out a fifteen day spiny lobster survey of the Pedro Bank in 2020 that sampled a portion of the Pedro Bank using traps (Figure 8). The sampling represented approximately sixteen per cent of the total bank. Coverage was limited due to financial and other resource constraints. The bank was gridded in fifty-eight 5km^2 squares covering a total area of the study is 1500km^2 . Traps were baited with cured cowhide cut into strips and fastened inside the trap utilising binding wire. Twenty-five traps were placed at 30-meter intervals and were linked by a rope. These 25 trap strings were then placed into each of the fifty-eight 5km^2 grid boxes with a soak time of three days. On the fourth day, each string was hauled and its contents recorded (Appendix 5 and 6). The spiny lobster body, carapace (head), tail, and body depth were weighed and measured to the nearest kilogram and centimetre. The sex was also determined as well as the female reproductive state/stage. All berried lobsters were thrown back. Only the total weight of that lobster was measured and not the individual weights of its head and tail.

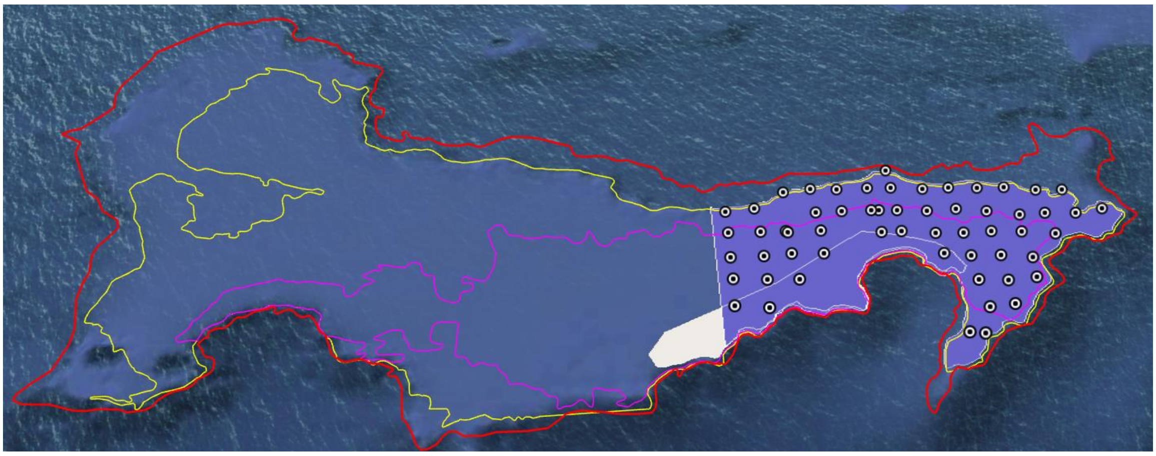

Figure 8: Pedro Bank showing study site (area shaded purple) and sample points. (NFA, 2021; Google, 2015)

2.5.2 Catch and effort data

Catch and effort data (Appendix 1) was taken from the National Fisheries Database and corroborated with the Veterinary Services Division (VSD) data. This data reflects total landings, the number of days spent at sea, the number of deployed traps per day and the processing level of the lobster landed.

2.5.3 Economic data

For the industrial spiny lobster fishing fleet, information on the costs associated with a lobster trip was acquired through interviews with industry members and supplemented with data taken from the Statistical Institute of Jamaica (STATIN, 2021).

2.6 Estimation of parameters

2.6.1 Biomass estimation

The total area of the Pedro Bank and each depth strata were obtained using Google Earth (Google, 2015), where polygons of the three depth strata (1–10 m, 11–20 m, and over 20 m) were measured (Figures 4 and 8). The sample design was a stratified random sampling technique (Smith & Tremblay, 2003), from which the per cent sampling area of the bank was determined. The effective fishing range of baited traps estimated according to Watson et al. (2009). Since the distance between each trap was 30m, the radius of the area fished by each trap was calculated to be 15m, resulting in a total area of 707m^2. The total weight of the lobsters caught by a string for each sample point was calculated. The mean was found for the entire surveyed area and then raised to the total area of the Pedro Bank for each depth zone. This result was then used to calculate the biomass of the total area by converting the figures to metric tonnes. This biomass estimate was used to calibrate the bioeconomic model and estimate the fishery parameter estimates (Appendix 7), which were then used to estimate the fishery reference points.

2.6.2 Biological parameters

The estimates of the parameters α and β were obtained by a regression method.

The catchability coefficient, θ, was computed from equation (V) where $\theta=q/ex$. The value for θ was calculated using total harvest, fishing effort and the biomass estimated from the survey data, done in 2020. The parameter K, carrying capacity, was calculated from the equations $K=\alpha/\theta$ and the parameter ρ, growth rate, was calculated from the equation $\rho=K\theta^2/\beta$. The fishery reference points were then calculated using these parameters. The catch per unit of effort (CPUE) was regressed against three measures of fishing effort, trap days, vessel numbers and days at sea, to determine the best fit. The catchability coefficient was then estimated from the survey data then expression IX was estimated. The key fishery reference points were then found for each effort measure.

2.6.3 Fixed costs

Fixed costs included capital costs such as vessel investment and associated gear as well as licencing fees. This information on costs was acquired through interviews of boat owners, industry representatives, boat captains, and from the National Fisheries Authority database. The exchange rate was obtained from the Bank of Jamaica in April 2021 (US$154), with an annual depreciation rate of 20% (Table 2).

Table 2: Jamaican spiny lobster average annual fixed costs

Type of Costs	Unit Cost (US$)	Description
Capital Cost	1,421,430	20% of capital cost
Vessel Registration Fees	6,642	
Total	**1,428,072**	**annual fixed cost**

2.6.4 Variable costs

The variable costs comprise those arising from fishing trips (crew remuneration, fuel, and food) and those associated with the catch at landing. The average fuel cost was computed by multiplying the total fuel used for a fishing trip by the 2021 diesel retail price of around US$1.32 per litre. The fishing crew cost was assumed to be 25% of the catch and an average of US$21,273 per trip. Finally, the variable annual costs are calculated based on a nine (9) month fishing season (July 1 – March 30) with an average of 84 trips per season at an average of 20 days at sea (Table 3).

Table 3: Variable costs associated with Jamaican Industrial spiny lobster fleet

Item	Unit price (US$)	Cost per trip (US$)	Annual Cost (US$)
Fuel	1.32/litre	8,380	754,220
Food and supplies	85/person	1,673	150,535
Traps	135/trap	11,043	993,870
Oil and Lubricants	9/day	177	15,939
Total Variable Costs		**21,273**	**1,898,625**

3 Data analysis and results

3.1 Biomass estimation and survey analysis

The estimates of biomass for the Pedro Bank and those for the sample site showed variation across depth strata (Table 4), with the deepest depths, >20m, showing the greatest quantities (Figure 9). The calculation of each depth strata can be found in Appendix 2 to 4. The carapace lengths (CL) of lobsters seen across all depths are most abundant for CLs ranging between 8.8 cm to 10.8 cm (Figure 9).

Table 4: Estimates of biomass (MT) for Pedro Bank, including sample site, for all depths (0m - >20m).

	Pedro Bank	**Sample Site**
	Biomass Total Depths (MT)	Biomass Total Depths (MT)
Upper CL (95%)	1,343	36
mean	943	25
Lower CL (95%)	543	14
	Biomass 20m (MT)	Biomass 20m (MT)
Upper CL (95%)	231	10
mean	123	5
Lower CL (95%)	16	1
	Biomass >20m (MT)	Biomass >20m (MT)
Upper CL (95%)	2,018	34
mean	1,442	25
Lower CL (95%)	865	15

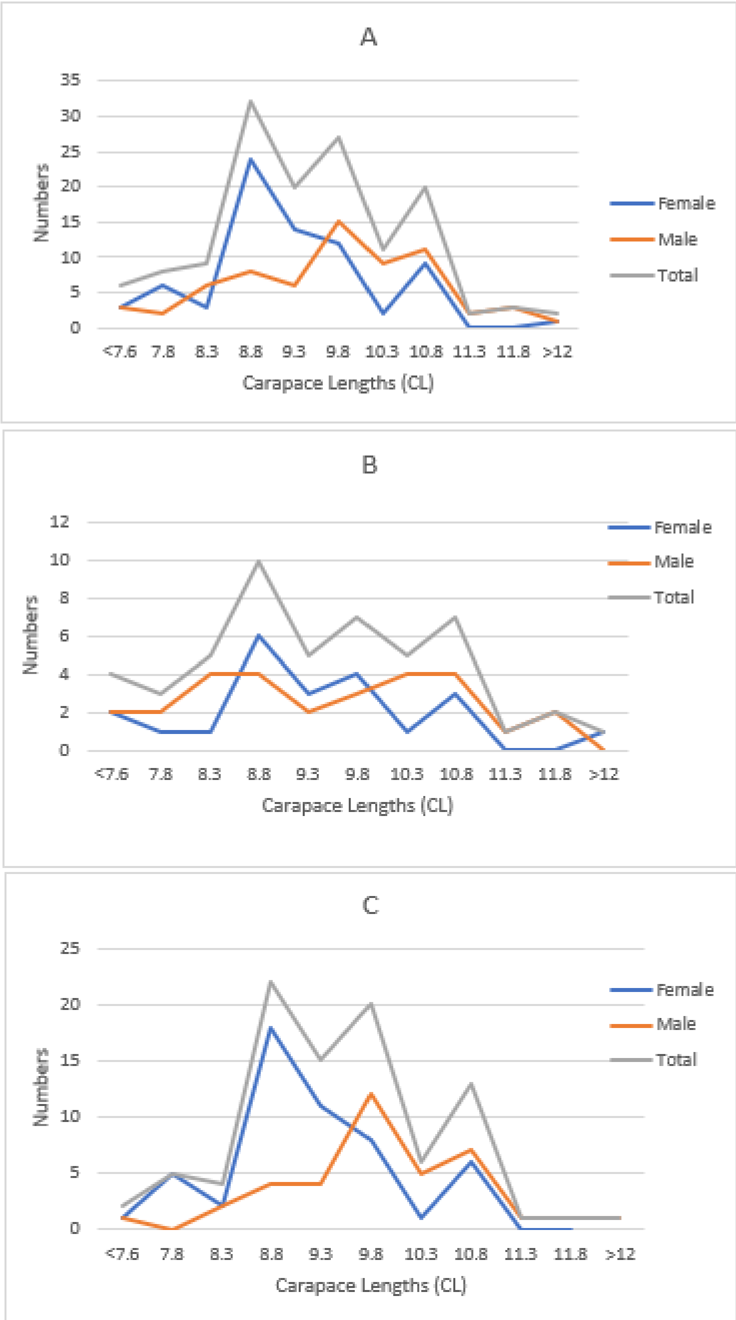

Figure 9: Carapace lengths (CL) of spiny lobster for: A - all depths (0m - >20m), B – 20m, C - >20m.

3.2 Reference points

Three (3) measures of effort, the number of trap days, the number of vessels, and days at sea (Figure 10), were examined to determine which measure was the best option for managing the fishery. Trap days established the most significant relationship with an R^2 of 0.96 and a p-value <0.05 (Table 5), with days at sea being the least significant. The number of trap days was also the most normally distributed measure when compared to the other estimates of effort. Each effort measure was then used to determine fishery reference points (Table 6). Appendix 7 outlines the parameters that were used to determine said reference points. Each MSY and MEY estimates were higher than the average catch of 301 mt observed over the past six (6) years. The E_{MSY} and E_{MEY} for trap days equated to 1,674 and 1,404 traps, respectively, at sixteen (16) vessels for 2020. In the E_{MSY} and $E_{MEY,}$ the number of days estimated for a trip would be 15 and 13, respectively. Regarding the other measures of effort E_{MSY} and E_{MEY}, the number of vessels was standardised at 15 vessels, whereas days at sea were 114 days and 113 days, respectively, for 16 vessels. Though not as high as trap days, the number of vessels was also a significant measure. Overall catch tends to be highest at the lowest levels of effort when all measures are compared.

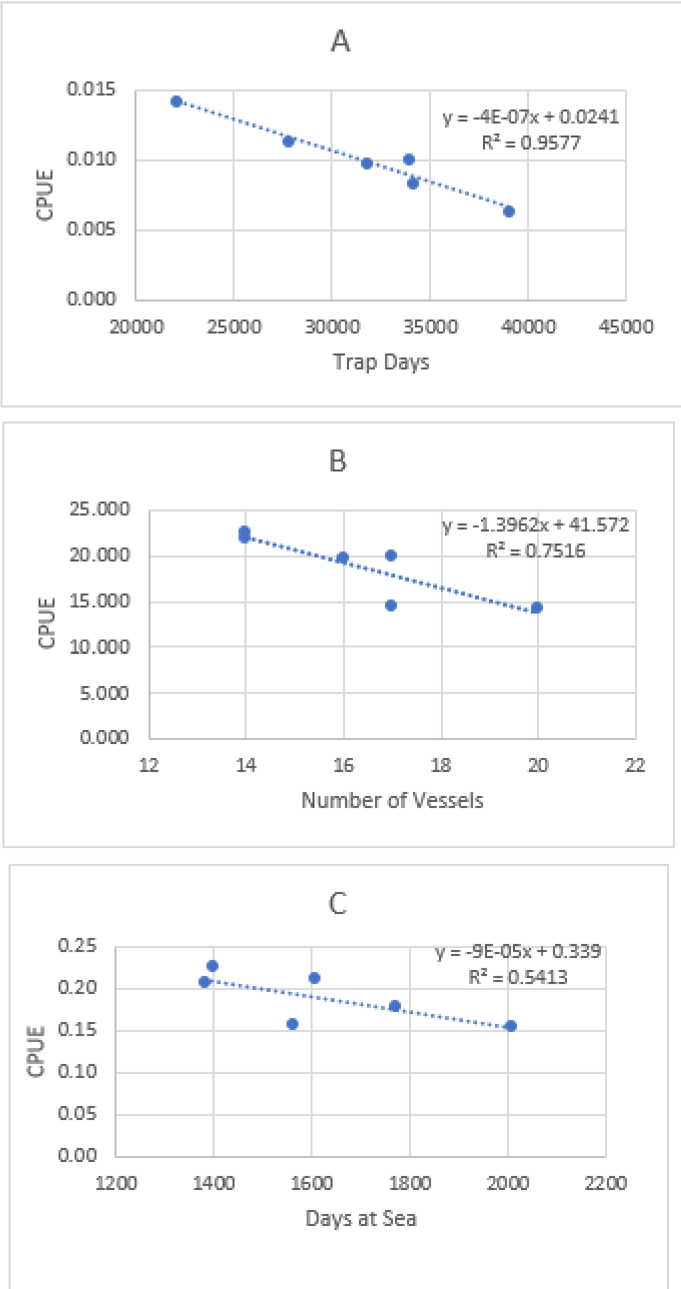

Figure 10: Relationship between three measures of fishing effort and catch per unit of effort. A – number of trap days, B – number of vessels, C – number of days at sea.

Table 5: Least squares result for three measures of effort.

	Trap Days	Number of Vessels	Days at Sea
R^2	0.96	0.75	0.54
Adjusted R^2	0.95	0.69	0.43
Coefficients	-0.0000004	-1.40	-0.0001
Standard Error	0.00000005	0.40	0.00004
t Stat	-9.52	-3.48	-2.17
P-value	0.001	0.03	0.10

Table 6: Key fisheries reference points for three measures of effort.

Coefficient	**Symbol**	**Trap Days**	**Number of Vessels**	**Days at Sea**
Carrying Capacity (MT)	**K**	1,598	1,995	1,800
MSY (MT)	**MSY**	323	309	309
Effort at MSY	$\mathbf{E_{MSY}}$	26,778	15	1,823
MEY (MT)	**MEY**	314	309	309
Effort at MEY	$\mathbf{E_{MEY}}$	22,472	15	1,802

3.3 Performance of indicators

Biomass increase from 2015 to 2018 according to the bioeconomic model, after 2019, it is predicted constant with an equilibrium around 930 mt, catches of around 33% of the biomass, and profits of just over US$2 million (Figure 11 and 12). Catch decreased from 2015 until 2017, after which there was a slight increase until 2019; after this, there was a slight decrease over time (Figure 11). Catch is also seen to be approximately 33% of the total biomass, reflecting MEY. The spiny lobster fishery saw its highest earnings in 2020 and its lowest in 2017 (Figure 12). 2017 dramatic decline resulted from it having the lowest catch (Figure 11), which came from a reduction in the number of vessels from 20 to 17. Profits are generally increasing after the industry's significant losses in 2017. Thus, the spiny lobster fishery is trending around the equilibrium point (US$2.2 m) at present. Appendix 8 shows the breakdown of the calculation used to generate this Figure 12. The sensitivity model (Figure 13) shows that the highest yields are generated at 20,000 trap days, a total that is less than the proposed MEY. The sensitivity model for the other measures of effort showed no future profits.

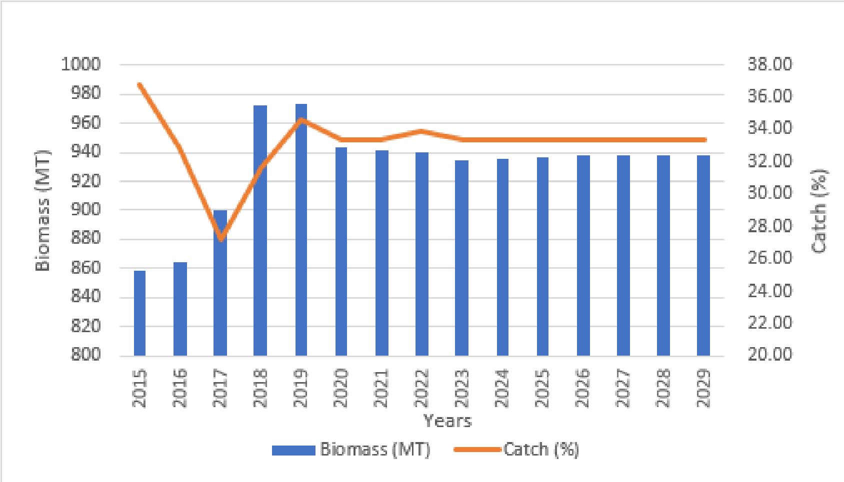

Figure 11: Catch as a percentage of biomass of spiny lobster over a 14 year period.

Figure 12: Future projection of profit trends for the spiny lobster fishery for the period 2015 to 2029.

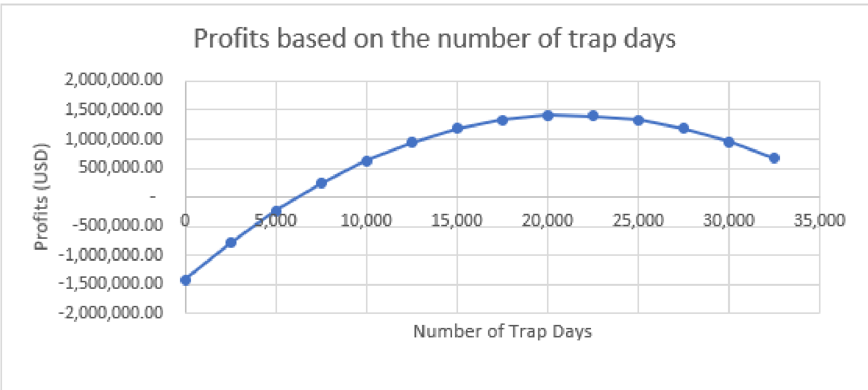

Figure 13: Sensitivity Model showing the various levels of profit based on the number of trap days.

4 Discussion

4.1 Biomass estimation and spiny lobster reference points

The biomass estimate calculated for this study may be considered preliminary given that the survey sampled only a portion of the area of the Pedro Bank. Notwithstanding, it represents the first, best and only fishery-independent estimation of spiny lobster biomass in Jamaica. The resulting fishery reference points are thus more reliable and accurate compared to the stock assessments by Haughton & King (1992), Martin-Murray (2009) and Morris (2010). Each resulted in overestimations of biomass due to the use of unreliable fishery-dependent data. The biomass and resultant MSY estimates from these stock assessments were less than that found in this study. Thus concluding that the fishery was overexploited, a situation in which this study seems to contradict as a result of this study MSY being larger than the average landings. The level of IUU fishing in Jamaica is an unknown variable for the lobster fishery (Morris, 2010). So the extraction level of the fishery is not known. Due to this it cannot be said that the fishery is not overexploited even though MSY estimates are below landings. That is why the accuracy and reliability of the results from this study can be further improved by increasing the survey sampling to reduce biases. That is completing the fishery independent survey for the entire Pedro Bank.

The survey saw larger numbers of lobsters sampled in the deeper areas of Pedro Bank, which is in keeping with the biology of lobsters, as the larger sized individuals tend to migrate to deeper waters, especially during their mating season (Fonseca-Larios & Briones-Fourzan, 1998). The survey was conducted in the closed season when reproduction is highest; thus, this study's results reflect what occurs at this time. The prevalence of the 8.8 cm carapace length individuals could be an indication of that cohort's success in recruiting to the fishery approximately three to two years ago, that is, 2017 or 2018. The fishery-dependent data was too short to distinguish any patterns in catch over time, that is, if there was a cyclical increase or decrease in catch over a period of time.

The MSY and MEY of the fishery are 323 mt and 314 mt respectively. The average lobster landing over the six-year period is 301 mt, suggesting that the fishery is operating below the sustainable yield. Notwithstanding the uncertainty regarding the impact of illegal, unreported and illegal (IUU) fishing, and those of the model, it would appear that catches tend to fall below MSY and MEY. Though the fishery may not be consistently over-exploited, that is its annual catches do not always exceed the MEY of 314 mt, IUU fishing could possibly make it overfished. This is why extraction levels need to be capped. Another issue that faces the lobster fishery is overcapitalisation. This is, evidenced by the number of recommended traps and vessels being less than the numbers currently being used (2,200 traps and 70 days per trip). The calculated improvement using 16 vessels would see the fishers using fewer traps at 1,400 and being out at sea for shorter trips at 13 days. Bearing this in mind, the regulatory agency would have to encourage the fishers to spend fewer days at sea by demonstrating an increase in profitability in their favour. Therefore, a proposed strategy is to encourage the fishers to agree to an effort reduction, establish a total allowable catch (TAC), and further split the TAC into quotas, which would secure each fishers harvesting ability for the fishing period. According to model predictions, a catch limit on the proposed TAC could be established as a 30% total of the biomass.

The spiny lobster fishery is relatively profitable at profits hovering just above US$2 m. To maintain optimum profit levels, the effort levels are currently operating above the recommended MEY effort. The effort levels should then be reduced to the suggested MEY level so that the fishery can have maximum benefits because the biomass is at its highest, which is favourable for the fishery.

Therefore, regulating the number of trap days appears to be an effective management tool. Thus, the current management focus utilising the number of vessels should be realigned to reflect an effort measure, the number of trap days, which should result in higher fishery performance. Overall this study has answered its research questions by establishing that trap days is the best management tool to control effort, and its associated MSY is 323 mt and MEY at 314.

4.2 Management direction

Jamaica’s vision 2030 (Government Of Jamaica, 2009) speaks of sustainably managing natural resources such as its spiny lobster fishery. This plan is in keeping with the sustainable development goal (SDG) 14 life below water, which focuses on sustainably utilising marine space (Kates et al., 2005). To move towards a more sustainably managed marine resource, a property rights-based structure is proposed to solve the Jamaican spiny lobster industry (Morris, 2010). To include a property rights-based regulatory framework inside the spiny lobster fishery, the common fisheries problem of a lack of such rights must first be rectified. Transferability, security, exclusivity, and permanence are qualities of such a system (Scott, 1996 & 2000 in Arnason, 2005). For such a framework, an individual quota system has been promoted as highly successful (Hannesson, 1993). The first step in putting such a system in place would be to establish a total allowable catch (TAC). Arnason (1993) recommended that to develop such a measure, a stock assessment or a study of past catches be performed first to define a boundary around those captures; individual quotas may then be determined from this TAC. This study conducted such an assessment to develop such a system. Implementing this system would allow spiny lobster fishers to prepare ahead of time and complete their fishing effort far more efficiently (Hannesson, 1993). Though the TAC is a beneficial measure, it must be combined with the individual quota system since it is a tool used to manage the "race to fish." The Icelandic Atlantic Mackerel fishery has such a precedent in that it was introduced without a quota system, resulting in a "race to fish" issue; it was not until 2010 that the quota system was implemented (Saevaldsson, H., & Gunnlaugsson, 2015) that it yielded improved management. The metrics that would therefore be used to determine whether or not this system is relevant and completely effective would be by watching how the fisheries performs via decreases in fishing effort and capture, with a consequent increase in the fishery's value (Runólfsson, B. Þ., & Árnason, 1996). Therefore, the onus will be on the NFA to ensure that all necessary checks and balances are in place to guarantee that the quota system functions appropriately.

As it stands, the Jamaica spiny lobster fishery current management system has not been adjusted over the years to ensure that its efforts are not in vain. Though the fishery is not overexploited, over-capitalisation is paramount and should be curtailed to increase profitability. Unless and until an individual quota system is implemented into the fishery's present regulatory framework, the Jamaican spiny lobster fishery will continue to proceed in an unsustainable manner. If the individual quota system is implemented, this fishery will be able to transition to a sustainably managed state and be eligible for prospective marine stewardship council (MSC) certification, increasing the value of the resource.

4.3 Limitations

Certain assumptions were made for the chosen model to work. These assumptions are as follows: lobsters were spread uniformly over the Pedro Bank, which is not the case for lobsters. In addition, the model used a high rate of growth, which indicates a rapid turnover of the stock, which may not be the case for lobster because it is a long-lived species. The price of lobster was also kept constant, which is not a feature of reality. Despite these limitations, it should be highlighted that this work uses fishery-independent data to produce a biomass estimate for the Jamaican spiny lobster, which has never been done before. This estimate serves as a baseline for future research to expand and enhance.

4.4 Conclusions

The fishery-independent survey needs to be completed to improve the results of this study. The study also established that the spiny lobster fishery current fishing levels, fall below the MSY and MEY. As a result of overcapitalisation, a reduction in effort is recommended. Trap days is the recommended effort measure to be used in the management of the spiny lobster fishery. The suggested ideal policy option is to manage the fishery through a TAC that incorporates an individual quota (IQ) system.

4.5 Recommendations

The recommendations for the Jamaican spiny lobster fishery are then to:

- Complete the spiny lobster survey that was started in 2020 so that the biomass estimate for the entire bank can be calculated instead of estimated.
- Consistent fishery-independent surveys over time will help to refine estimates further and build long term time series data essential features of well-managed fisheries.
- Using only 16 vessels, reduce overcapitalisation in the fishery by reducing the number of traps and the number of days spent at sea.
- Set a total allowable catch (TAC) at 314 mt.
- Establish the appropriate management framework to develop an individual quota-based structure.
- Continue with data collection efforts of spiny lobster landings and include financial information on the price of lobster.

5 Acknowledgement

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6 References

Aiken, K. A. (1983). Further investigations of the Jamaica spiny lobster fishery. *FAO Fisheries Report*, *278*, 177–191.

Arnason, R. (2005). Property rights in fisheries: Iceland's experience with ITQs. *Reviews in Fish Biology and Fisheries*, *15*(3), 243–264. https://doi.org/10.1007/s11160-005-5139-6

Brey, T., & Pauly, D. (1986). *Electronic length frequency analysis* (A revised and expanded user's guide to ELEFAN 0, 1 and 2). ICLARM.

Chakalall, B., & Cochrane, K. (2007). Regional cooperation for the responsible use of the caribbean spiny lobster resource. *Proceedings of the 60th Gulf and Caribbean Fisheries Institute*, *60*, 239–246.

Chavez, E. (2007). Socio-economic assessment for the management of the caribbean spiny lobster. *Proceedings of the 60th Gulf and Caribbean Fisheries Institute*, *60*, 193-196.

Cooke-Panton, K. (2014). *An analysis of puerulus settlement of the caribbean spiny lobster (Panulirus argus) stock in Jamaica with practical management recommendations*. United Nation University Fisheries Training Program.

CRFM. (2007). Report of Third Annual Scientific Meeting. In *Caribbean Regional Fisheries Mechanism Secretariat* (Vol. 1, Issue July).

CRFM. (2009). *Report of Fifth Annual Scientific Meeting - Kingstown, St. Vincent and the Grenadines, 09-18 June 2009 _ Fishery Management Advisory Summaries.*

Ehrhardt, N., Puga, R., & Butler, M. (2011). Implications of the ecosystem approach to fisheries management in large ecosystems. The case of the caribbean spiny lobster. In L. Fanning, R. Mahon, & P. McConney (Eds.), *Towards marine ecosystem-based management in the wider Caribbean* (MARE, pp. 157–175). Amsterdam University Press. https://doi.org/10.1017/9789048512805.014

FAO. (2021). *Fishery and Aquaculture Country Profiles Jamaica. Country Profile Fact Sheets. Fisheries and Aquaculture Division [online].* Rome. https://www.fao.org/fishery/en/facp/jam?lang=en

Fonseca-Larios, M. E., & Briones-Fourzan, P. (1998). Fecundity of the spiny lobster Panulirus argus (Latreille , 1804 in the Caribbean Coast of Mexico. *Bulletin of Marine Science*, *63*(July 1998), 21–32.

https://www.researchgate.net/publication/233555389_Fecundity_of_the_spiny_lobster_Panulirus_argus_Latreille_1804_in_the_Caribbean_Coast_of_Mexico

Gittens, L. (2001). *An assessment of recent (1996-2000) biological and socieconomic characteristics of the Jamaican lobster (Panulirus argus) fishery, with implications for future management.* University of the West Indies.

Google. (2015). *Google Earth Landsat Image* (Google Earth Pro). GEBCO. https://earth.google.com/web/@16.00035088,-78.20056588,133913.23586524a,0d,35y,-0h,43.833t,-0r?utm_source=earth7&utm_campaign=vine&hl=en

Government Of Jamaica. (2009). *Vision 2030 Jamaica*. http://lslandr.com/vision2030/vision-2030-jamaica-sector-plans/

Hannesson, R. (1993). *Bioeconomic Analysis of Fisheries* (FAO (ed.)). Fishing New Books.

Haughton, M. O., & Shaul, W. (1989). Estimation of growth parameters for spiny lobster (Palinurus argus) in Jamaican waters. In *Proceedings gulf and caribbean fisheries institute* (Vol. 39, pp. 279–288).

Hutchinson, S. D., & Girvan, A. S. T. (2021). *Jamaica Caribbean Spiny Lobster Value Chain Analysis Report*.

Jones, R. (1984). *Assessing the effects of changes in exploitation pattern using length composition data (with notes on VPA and chohort analysis).*

Kates, R. W., Parris, T. M., & Leiserowitz, A. A. (2005). What is sustainable development? Goals, indicators, values, and practice. *Environment*, *47*(3), 8–21. https://doi.org/10.1080/00139157.2005.10524444

Kelly, R. (2002). *Report on the spiny lobster fishery in Jamaica in report of the second workshop on the Management of Caribbean Spiny Lobster Fisheries in WECAFC Area*.

Knútsson, Ö., Kristófersson, D. M., & Gestsson, H. (2016). The effects of fisheries management on the Icelandic demersal fish value chain. *Marine Policy*, *63*, 172–179. https://doi.org/10.1016/j.marpol.2015.03.015

Larkin, S. L., Milon, J. W., & Ehrhardt, N. M. (2002). *Bioeconomic Models of the Florida Commercial Spiny Lobster Fishery* (D. Letson & J. W. Milon (eds.)). https://earthmind.org/sites/default/files/2002-

FloridaCoastalResourcesEconomicValuationImpactAnalysis.pdf#page=157

Leahy, S. (2010). *Locally-Run protected areas could reverse fisheries death spiral*. UXBRIDGE. http://stephenleahy.net/2010/10/04locally-runprotected-area-could-reverse-fisheries-death-spiral/

Martin-Murray, A. O. (2009). *The use of production models and length frequency data in stock assessments in Jamaica fisheries, building on the Caribbean spiny lobster observations.* United Nations University - Fisheries Training Programme.

Marx, J. M., & Herrnkind, W. F. (1985). Macroalgae (Rhodophyta: Laurencia spp.) as habitat for young juvenile spiny lobsters, Panulirus argus. *Bulletin of Marine Science*, 423–431.

Meggs, L. G. C., Steele, R. D., & Aiken, K. A. (2010). Settlement patterns of spiny lobster (Panulirus argus) postlarvae on collectors in jamaican waters and culture of juveniles. *Proceedings of the 63rd Gulf and Caribbean Fisheries Institute*, *63*, 472–481. http://nsgl.gso.uri.edu/flsgp/flsgpw10002/data/papers/087.pdf

Morris, R. A. (2010). *A Bioeconomic analysis of the Jamaican Industrial Spiny Lobster (Panulirus argus) Fishery*. United Nations University Fisheries Training Programme.

Munro, J. (1974). The Biology, Ecology and Bionomics of the Spiny Lobster (Palinuridae), Spider Crabs (Majiidae) and other Crustacean Resources. *ICLARM Studies and Reviews 7*, 206–222.

National Fisheries Authority. (2020a). *Lobster fishery regime*. Ministry of Agriculture and Fisheries. https://www.moa.gov.jm/content/fisheries-and-aquaculture

National Fisheries Authority. (2020b). *The fishing industry act*. Ministry of Agriculture and Fisheries. https://www.moa.gov.jm/content/fisheries-and-aquaculture

National Fisheries Authority. (2021). *Data unit*.

Runólfsson, B. Þ., & Árnason, R. (1996). ITQs in Iceland: A descriptive account evolution and performance of the Icelandic ITQ system. *In Icelandic Economic Paper*. https://notendur.hi.is//~bthru/iceitq1.html

Saevaldsson, H., & Gunnlaugsson, S. B. (2015). The Icelandic pelagic sector and its development under an ITQ management system. *Science Direct.*, 21–52.

Smith, S. J., & Tremblay, M. J. (2003). Fishery-independent trap surveys of lobsters (Homarus americanus): Design considerations. *Fisheries Research*, *62*(1), 65–75.

https://doi.org/10.1016/S0165-7836(02)00251-5

Sparre, P. (1987). *Computer programs for fish stock. Length-based fish stock assessment (LFSA)*.

STATIN. (2021). *Statistical Institute of Jamaica*. https://statinja.gov.jm/

Watson, W. H., Golet, W., Scopel, D., & Jury, S. (2009). Use of ultrasonic telemetry to determine the area of bait influence and trapping area of American lobster, Homarus americanus, traps. *New Zealand Journal of Marine and Freshwater Research*, *43*(1), 411–418. https://doi.org/10.1080/00288330909510010

WECAFC. (2007). *Report of the Fifth Workshop on the Management of the Caribbean Spiny Lobster*.

7 Appendix

Appendix 1: Spiny lobster fishery data for the period 2015 - 2020

Fishing Season	Total Vessels	Total Crew Size	Average Vessel Size (m)	Total trips per vessel	Total Days at Sea	Total Fuel Usage (gallons)	Total Traps Hauled (per day)	Total Catch (lbs)	Total Catch (tonnes)
2015	14	452	22	66	1398	173155	27800	695318	315
2016	20	536	15	101	1381	156276	34120	626695	284
2017	17	487	18	72	1564	176484	39060	540840	245
2018	14	660	21	105	2006	249740	31850	677334	307
2019	17	627	19	71	1606	149247	33977	743066	337
2020	16	466	20	90	1771	150844	22118	693439	315

Appendix 2: Fishery Independent Survey results for all depths (0m - >20m)

Strings	Number of traps retrieved	Weight (kg)	Weight (kg/trap)	Weight per baited trap (kg/m2)
LQ07	24	1.97	0.08	0.0001
LQ08	17	0.79	0.05	0.0001
LQ22	18	0.45	0.03	0.0000
LQ23	24	1.25	0.05	0.0001
LQ25	25	0.57	0.02	0.0000
LQ27	21	2.95	0.14	0.0002
LQ34	21	4.20	0.20	0.0003
LQ35	22	1.59	0.07	0.0001
LQ37	23	1.02	0.04	0.0001
LQ40	23	6.80	0.30	0.0004
LQ41	25	2.15	0.09	0.0001
LQ42	24	11.91	0.50	0.0007
LQ43	22	5.44	0.25	0.0003
LQ44	23	0.23	0.01	0.0000
LQ45	25	1.93	0.08	0.0001
LQ47	25	2.04	0.08	0.0001
LQ48	13	3.97	0.31	0.0004
LQ49	12	1.13	0.09	0.0001
LQ51	18	7.26	0.40	0.0006
LQ52	20	1.25	0.06	0.0001
LQ53	20	6.92	0.35	0.0005
LQ54	20	5.67	0.28	0.0004
LQ55	20	3.86	0.19	0.0003
LQ56	25	6.92	0.28	0.0004
LQ57	45	12.58	0.28	0.0004
LQ58	25	4.31	0.17	0.0002
Total	**580**	**99.1**	**4.4**	**0.006**

Appendix 3: Fishery Independent Survey results for 20m Depth Zone

Strings	Number of traps retrieved	Weight (kg)	Weight (kg/trap)	Weight per baited trap (kg/m2)
20m				
LQ07	24	1.97	0.08	0.0001
LQ08	17	0.79	0.05	0.00007
LQ22	18	0.45	0.03	0.00004
LQ25	25	0.57	0.02	0.00003
LQ27	21	2.95	0.14	0.00020
LQ44	23	0.23	0.01	0.00001
LQ45	25	1.93	0.08	0.00011
LQ48	13	3.97	0.31	0.00043
LQ49	12	1.13	0.09	0.00013
LQ51	18	7.26	0.40	0.00057

Appendix 4 Fishery Independent Survey results for >20m Depth Zone

Strings	Number of traps retrieved	Weight (kg)	Weight (kg/trap)	Weight per baited trap (kg/m2)
>20m				
LQ23	24	1.25	0.05	0.0001
LQ34	21	4.20	0.20	0.0003
LQ35	22	1.59	0.07	0.0001
LQ37	23	1.02	0.04	0.0001
LQ40	23	6.80	0.30	0.0004
LQ41	25	2.15	0.09	0.0001
LQ42	24	11.91	0.50	0.0007
LQ43	22	5.44	0.25	0.0003
LQ47	25	2.04	0.08	0.0001
LQ52	20	1.25	0.06	0.0001
LQ53	20	6.92	0.35	0.0005
LQ54	20	5.67	0.28	0.0004
LQ55	20	3.86	0.19	0.0003
LQ56	25	6.92	0.28	0.0004
LQ57	45	12.58	0.28	0.0004
LQ58	25	4.31	0.17	0.0002

Appendix 5: Fishery Independent Survey Data Form

NATIONAL FISHERIES AUTHORITY
MINISTRY OF INDUSTRY, COMMERCE, AGRICULTURE & FISHERIES
LOBSTER SURVEY DATA COLLECTION

DATA ENTRY ONLY	
ENTERED	*CHECKED*
DATE	*DATE*
BY	*BY*

GRID (BOX) ID #: ____________ **DEPTH (Ft/m):** ____________ **DATE OF DEPLOYMENT:** ____________

GPS Coordinate: N ____________ **W** ____________ **DATE OF HARVEST:** ____________

STRING ID #:		**STRING ID #:**		**STRING ID #:**	
LOBSTER		**LOBSTER**		**LOBSTER**	
Weight (lbs)	Count	Weight (lbs)	Count	Weight (lbs)	Count

BY-CATCH		**BY-CATCH**		**BY-CATCH**	
Species Caught (*including crabs and other species*)	Count	Species Caught (*including crabs and other species*)	Count	Species Caught (*including crabs and other species*)	Count

Appendix 6: Fishery Independent Survey biological data form

NATIONAL FISHERIES AUTHORITY
MINISTRY OF INDUSTRY, COMMERCE, AGRICULTURE & FISHERIES
LOBSTER SURVEY BIOLOGICAL DATA COLLECTION FORM

DATA ENTRY ONLY	
ENTERED	CHECKED
DATE	DATE
BY	BY

	STRING ID #:	(M/F)	Maturity (T D E S)	Length (cm)			Weight (lbs)		
				Carapace	Tail	Total	Carapace	Tail	Total
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									

Maturity: T - female with tar, D – female with orange eggs, E - female with brown eggs S -female with scratched tar only.

Appendix 7: Parameters used to calculate the fishery reference points.

Parameters	Symbol	Value
alpha	α	0.02
Beta	β	-0.0000004
Catch (tonne)	q	314.5
Effort (traps hauled per day)	e	22,118
Biomass (tonne)	x	943
Catchability	θ	0.00002
Carrying Capacity (tonne)	κ	1598
Growth Rate	ρ	0.8
Price (usd/tonne)	P	22,333
Cost (usd/trip)	c	87

Appendix 8: Bioeconomic outputs simulated for the period 2015 - 2029

Years	x (tonne)	G(x) (tonne)	e (trap days)	q (tonne)	revenue (US$)	cost (US$)	Profits (US$)
2015	859	321	27800	315	7,043,727	5,079,405	1,964,323
2016	864	321	34120	284	6,348,554	6,454,794	- 106,240
2017	900	318	39060	245	5,478,825	7,135,267	- 1,656,442
2018	973	308	31850	307	6,861,539	5,713,345	1,148,194
2019	973	307	33977	337	7,527,427	6,375,611	1,151,816
2020	943	312	22118	315	7,024,686	4,769,114	2,255,572
2021	941	313	22118	314	7,007,295	4,764,767	2,242,528
2022	940	313	22472	318	7,110,068	4,819,431	2,290,638
2023	934	313	22118	311	6,956,152	4,751,981	2,204,171
2024	936	313	22118	312	6,971,267	4,755,760	2,215,507
2025	937	313	22118	313	6,979,267	4,757,760	2,221,508
2026	938	313	22118	313	6,983,490	4,758,815	2,224,674
2027	938	313	22118	313	6,985,714	4,759,371	2,226,343
2028	938	313	22118	313	6,986,886	4,759,664	2,227,221
2029	938	313	22118	313	6,987,502	4,759,818	2,227,684