

Department of Environment and Agriculture

**Sustainability of Lobster *Panulirus argus* Fisheries in Marine Protected Areas
in South-eastern Mexico**

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(Kim Ley-Cooper)

This thesis is presented for the Degree of

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DECLARATION

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university, except some figures that were published in co-authorship with Nathan Truelove from Manchester University involving genetic studies which we carried out together during the development of this thesis.

Kim Ley (*Ley-Cooper, Kim*)

June 2015

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Beyond this, I do not wish to place any restrictions on this thesis.

Kim Ley (*Ley-Cooper Kim*)

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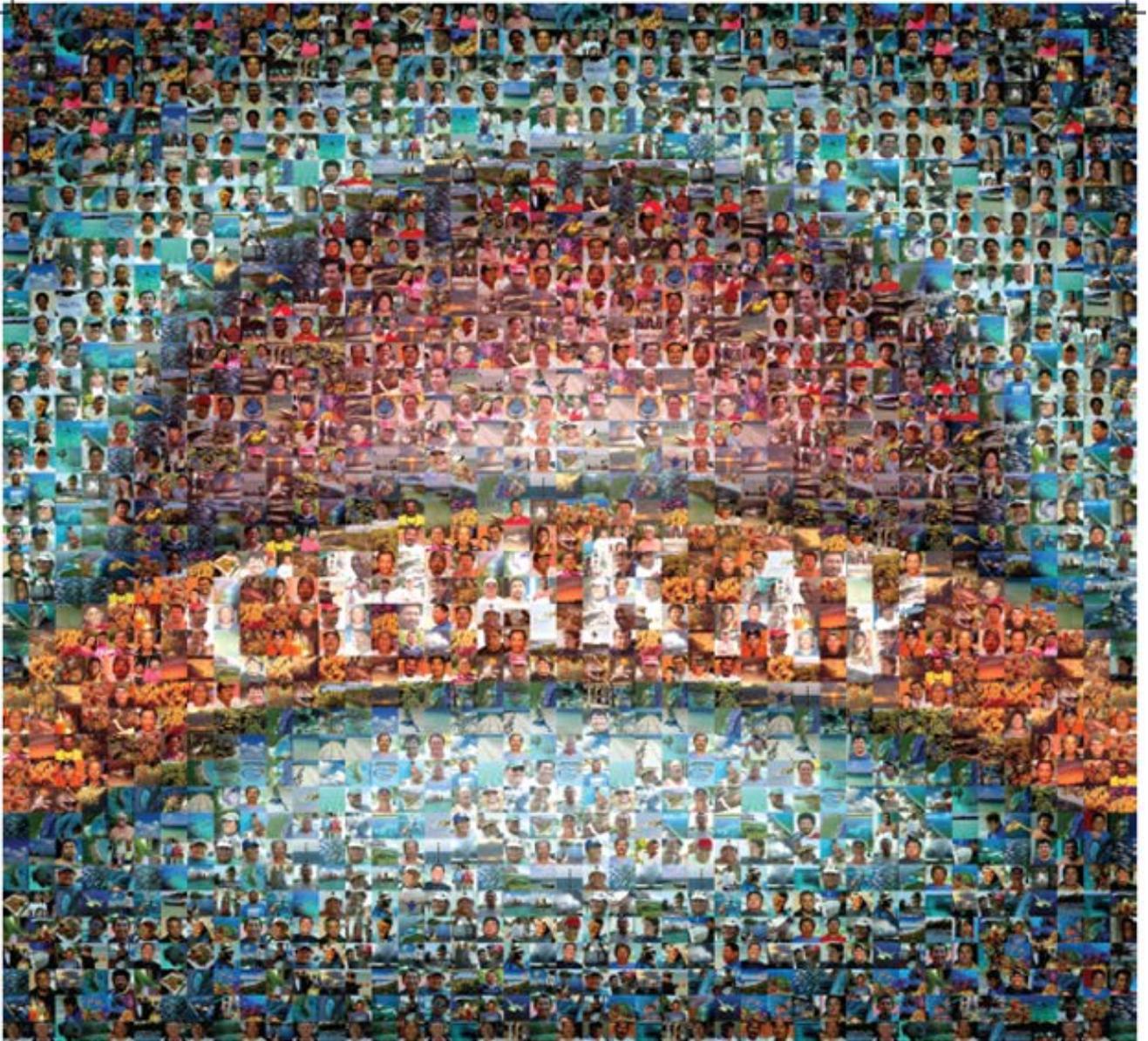
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descubre un tesoro del mar Caribe...

Chakay, langosta de pesca sustentable

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LIST OF ABBREVIATIONS

| Abbreviation | Name | Abbreviation | Name |
|--------------|---|-----------------|----------------------------------|
| BA | Bahía de la Ascensión in North Sian Ka'an | mm | millimetre |
| BC: | Banco Chinchorro Biosphere Reserve | NGO | Non-Governmental Organization |
| BES | Bahía del Espíritu Santo in South Sian Ka'an | PLD | Pelagic Larval Duration |
| cm | Centimetre | <i>P. argus</i> | <i>Panulirus argus</i> |
| CL: | Carapace Length | TW | Tail Weight (<i>P. argus</i>) |
| CPC | Coral Point Count | SK: | Sian Ka'an Biosphere Reserve |
| CPE | Coral Point-Count with Excel | RGR | Relative growth rate |
| CPUE: | Catch Per Unit of Effort | WW | Whole weight (<i>P. argus</i>) |
| F | Fishing mortality | | |
| g | gram | | |
| HCR | Harvest Control Rules | | |
| IPQR. | Integradora de Pescadores de Quintana Roo. | | |
| kg | Kilogram | | |
| M | Natural mortality | | |
| m | metre | | |
| min | Minute | | |
| MBRS | Mesoamerican Barrier Reef System | | |
| MSC | Marine Stewardship Council | | |
| MPA | Marine Protected Areas | | |
| | | | |

LIST OF ANIMALS

Caribbean spiny lobster (*Panulirus argus*), Western rock lobster (*Panulirus cygnus*), Spotted spiny lobster (*Panulirus guttatus*), Red lobster (*Panulirus interruptus*), Homarus (*Homarus americanus*)

PREAMBLE

This thesis consists of nine full chapters, and additional section on future research and monitoring, as well as a series of annexes as complementary information.

Chapter 1 reviews the existing literature on the topics related to the general biology of *P. argus* lobster including, taxonomy, biology, ecology and population dynamics. Important aspects on regional and local fisheries and stock criteria for assessing sustainability aspects, especially for the SK and BC fisheries are revised. Current management measures and social arrangements are discussed, as well as the use of research methods to evaluate and assess these populations. Some figures and material published in co-authorship as a result of work carried out during the development of this thesis are also detailed, presented and discussed in this section, as they are of relevance to this study and specifically referred to in the discussion of this thesis but not included in chapters elsewhere; specifically applies to sections on population genetics (section 1.5) (Truelove 2014, Truelove et al. 2014, Truelove et al. 2015), and Bio-economic modelling Fishery Simulation Model-FISMO in BC (Section 0) (Ley-Cooper & Chávez 2009).

Chapter 2 is the general introduction to the thesis where the general aims and objectives are described as an introduction that underlines the importance of this study.

Chapter 3 describes the general materials and methods employed throughout the different stages of this research project, including how fisheries dependent data was gathered and how independent surveys were designed and implemented in general terms. However, all sections where experiments and field work were carried out contain the detailed methods used within each chapter.

Chapters 4 – 8 have been produced during the course of this thesis and have already been published partially or completely either in peer reviewed journals, conference papers, or have been submitted and are currently under review. These represent the core sections of the research. They may contain some duplicated information in the introduction because they are sections which were created to be read independently. Reference style in these chapters has been standardized to fit this thesis, and therefore modified from to the Journal where they were published or submitted. Since all these chapters have been presented at international conferences or independently submitted to peer-reviewed journals for the publication, some of the basic information presented in introduction section in these chapters may be repetitive

in nature. Editorial changes have been made in order to fit the thesis format and logical sequence of figures and chapters numbers. In certain sections of Chapter 8, some published information (Ley-Cooper 2010), has been modified accordingly to update it to the current situation in 2015.

Chapter 9 constitutes the discussion section and brings all the relevant results together by discussing the overarching conclusions and recommendations. This chapter includes further analysis in some sections by extracting the main results from the previous chapters in order to highlight the main conclusions of the research project and discuss the limitations. Within the framework of this study, the discussion section follows a logical order similar to the principles and criteria used by Marine Stewardship Council, in order to revise, evaluate and analyse sustainability of the Sian Ka'an and Banco Chinchorro fisheries in a more comprehensive manner. The Chapter presents some conclusions and recommendations for future monitoring, research and management which are summarized in the last section 10.

Note regarding Co-authorship and acknowledgements:

Co-authorship and acknowledgements of collaborative work carried out with my supervisors and other colleagues has been specified and evidenced throughout the thesis. This becomes explicit by citing the original paper and giving credit to the authors as in section 1.5 (genetics), or by a note under the title as in chapters 4, 5, 6 and 7. The corresponding papers which have been published in co-authorship are also listed in Section 13. Throughout the development my thesis project, besides my supervisors I closely collaborated with several colleagues at different level such as:

- Dr. Simon de Iestang for stock assessment and modelling the fisheries dynamics, from WA Fisheries Department.
- Dr. Patricia Briones *P.argus* population dynamics, as well as use and of Casitas occupation from U.N.A.M.
- Dr. Ernesto A. Chavez for Bio-economic assessment
- Dr. Lynda Bellchambers for assessing habitat and MSC principles from WA Fisheries Department,
- Dr. Nathan Truelove from Manchester University (population genetics).

Depending on each case, the contributions of each co-author to the resulting articles varied from research design, to application of new methods and materials, to lab work, data analysis, or even result interpretation. The level of contribution has been acknowledged and directly attributed to the level of contribution in each case. Publications where I (Ley-Cooper) appeared as second or third

author were in some cases referred to in detail in the thesis either in the literature review section or in the discussion. For publications included as chapters 4, 5, 6 and 7 of the thesis where I have been first author, all field work, data gathering, analysis and interpretation of results was either coordinated and/or directly carried out by me, and helped by a variable number colleagues, research team members, or technicians involved at different stages of the project. In some cases projects included participation of fisher cooperatives for fishery related data such as landings and biometrics, as well as tag recaptures which were otherwise mentioned in the acknowledgement sections. The whole research framework, series of tasks and activities required to complete the peer reviewed publications were also coordinated by me with the required feedback and conceptual input given my supervisors/co-authors. I have explicitly acknowledged Dr. de lestant's contribution to the complex modelling methods and data analysis coded in the program "R" which constituted a substantial involvement in the papers where he was assigned as second author.

ABSTRACT

Panulirus argus constitutes the most highly valued marine species within the Biosphere Reserves of Sian Ka'an (SK) and Banco Chinchorro (BC) in the South-eastern Mexican Caribbean, and these are the first fisheries in the world for this species to have been certified as being sustainable by the Marine Stewardship Council (MSC). In this study sustainability of these fisheries is assessed from a biological, ecological, environmental, social and economic perspective, by including population dynamics evaluations and assessing the status of the stocks using several techniques. Biological aspects such as movements and migration patterns of this species were examined by mark and recapture tagging studies, which were also used for developing stock assessment modelling methods and evaluating exploitation rates. Fishery dependent data and information from fishery independent surveys were combined and evaluated by developing unique fishery models for analysis. Results produced information regarding the status of the lobster stocks and local populations, including biological reference points useful for evaluating the ecolabelling sustainability principles and criteria currently applied to these fisheries. Research included an analysis of the potential effects of introducing artificial refuge/casitas into BC as a new fishing gear for live lobster capture, and as a means for enhancing juvenile survival and recruitment to the fishery. Management, social stewardship, value addition and socio-economic aspects of these fisheries were also analysed in relation to the implementation of the ecolabelling programs: "Chakay" and MSC. Results from this study provide a better understanding of the lobster populations of *P. argus* at a regional and local scale, as well as long term sustainability needs of these Marine Protected Areas and other spiny lobster fisheries in the Caribbean. Suggestions for implementing management measures and future research are suggested for the SK and BC *P. argus* populations, which could potentially improve the fisher cooperatives economic condition, and the livelihoods of the fishers associated to these fisheries.

1 CHAPTER 1: Literature Review

1.1 Background

Most fished species, including the *Panulirus argus* lobster are being depleted or have high risk levels for overexploitation around the world (Jackson et al. 2001, Ehrhardt & Fitchett 2010, FAO 2011, Groeneveld et al. 2013). This has become a growing concern for stakeholders involved in industry, environmental conservation organizations, fishery management agencies and research institutions around the Caribbean and Mesoamerican Reef (Pauly et al. 2002b, Caddy & Seijo 2005, Seijo 2007, Gardner et al. 2013, Phillips 2013). Generally a series of wide-ranging research programs have been implemented in order to maintain sustainability of spiny lobster fisheries, as these have been subject to intensive fishing (Phillips et al. 2013). Currently, spiny lobster *P. argus* fisheries are considered either stable, fully, or overexploited throughout the species' range (FAO 2011, Groeneveld et al. 2013, Phillips et al. 2013). However the true global catch of lobsters may considerably exceed that disclosed in the reported statistics, as subsistence and locally traded catch is only weakly accounted for in catch statistics, and therefore likely to be underestimated (Ward & Phillips 2013).

Many stakeholders directly involved in fishing activities have made considerable efforts to partake in sustainable fishing practices attempting to manage stocks in order to mitigate rapid depletion (Cinner et al. 2009, Ward & Phillips 2010, Bellchambers et al. 2014), although this is very complex (Caddy & Seijo 2005, Agnew et al. 2013). Initiatives include certifying and ecolabelling of seafood products as a marketing strategy (Ward & Phillips 2013), as implemented by the lobster fisheries in Banco Chinchorro (BC) and Sian Ka'an (SK) Mexico, which have a nationally recognized eco-label "Chakay" (Ley-Cooper 2010, Ward & Phillips 2010) recently certified as sustainable by the Marine Stewardship Council (MSC) (MRAG-Americas 2012, MSC 2014).

In order to change the trend among fisheries to decline, new solutions based on scientific research are needed, as these represent fundamental tools for increasing understanding of the various challenges they face (Pauly et al. 2002b, Seijo 2007, Gardner et al. 2013). Assessments from research studies should enable stakeholders to act upon these results effectively proposing alternative management strategies (Walters 2000, Caddy & Seijo 2005, Penn et al. 2015). Gardner et al. (2013) state that an effective way of

incorporating alternative strategies and solutions to solve issues related to the sustainability of fisheries requires a comprehensive analysis of different components of the fished populations, and should ideally include: a) assessment of biological aspects of the fished species including ecological characteristics and behavioural traits throughout the life cycle; b) understanding of both the impact of the fishery on the environment, habitat and associated species, as well as the effects of the environment on the fishery at all levels; c) scientific assessment of stock status and dynamics of the fished populations at a regional and local level, including recruitment and connectivity; and d) and evaluation of the socioeconomic and cultural aspects regarding the use and practices of the fished resource (Bellchambers et al. 2009, Annalana & Eayrs 2010, Jacquet et al. 2010, Pauly et al. 2013, Bellchambers et al. 2014, Velez 2014). The latter are all interwoven components that affect the complex management required for sustaining lobster fisheries (Sosa-Cordero et al. 2008, de Lestang et al. 2012, Phillips et al. 2013, Puga et al. 2013) . Likewise this is also the motivation of this thesis and the focus of this literature review.

Critical factors for achieving well-managed fisheries include controlling overfishing, and reducing illegal fishing by assuring compliance with existing legislation (Penn et al. 1997, Donohue et al. 2010, Ríos-Lara et al. 2012). In the biogeographic region known as the Mesoamerican Barrier Reef System (MBRS) found in the Central American portion of the Caribbean (Figure 1-10) (Seijo 2007, Muhling et al. 2013), initiatives to encourage the sustainability of fisheries have included changes in policy, legislation and innovations in management systems, in some cases incorporating an ecosystem based approach to conservation (Arce et al. 2001, Ley-Cooper 2010). The latter has included the establishment of specific and regional management programs (Ríos-Lara et al. 2012), implementation of Marine Protected Areas (MPA's) (INE-SEMARNAP 2000, Ley-Cooper 2006, CONANP 2007 , Little et al. 2011, Origlio et al. 2014) and the application of strategies such as unfished areas and no take- zones (NTZ) (Lozano-Álvarez et al. 1993, Lozano-Álvarez 1995, Briones-Fourzán et al. 2000, Acosta & Robertson 2003, Caddy & Seijo 2005, Bertelsen 2013, Ley-Cooper et al. 2014, Velez 2014).

Attempts to improve management and conservation of specific areas and ecosystems, have resulted in the creation of Marine Protected Areas (MPA's), regarded as a tool for restocking fished populations and restoring habitats (Walters 2000, Ezer et al. 2005, Goñi et al. 2010, Muhling et al. 2013). The BC and SK Biosphere Reserves are MPA's Found in the South Central Mexican Caribbean portion the MBRS, where access to fisheries is limited to

six cooperatives and controlled by park and management authorities (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 2008, MRAG-Americas 2012, Ley-Cooper et al. 2013). These are regarded as two of the most important Mexican MPA's in the MBRS region in terms of their ecosystem components, levels of biodiversity and a size of 528,000 ha and 144,360 ha respectively. In 2012 the SK and BC were granted the certification of sustainability (Ley-Cooper 2010, MRAG-Americas 2013), for complying with criteria established by the MSC which takes into account the way fisheries are managed (INE-SEMARNAP 2000, Seijo 2007, CONANP 2007, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013).

Certification of seafood and ecolabelling systems (Ward & Phillips 2010) is becoming increasingly popular and over nine lobster fisheries are either certified or currently being assessed by the MSC programme (MSC 2014). These programs generally aim to evaluate and guide stakeholders to achieve sustainability with regard to fishery management and maintenance of stocks, whilst also considering environmental aspects of the ecosystem and associated species; although ecolabels are diverse and wide ranging in terms of different components (Ward & Phillips 2013). The certification potential of sustainable fishing ecolabels that range from national initiatives such as the Mexican Chakay lobster eco-label in BC and SK (Ley-Cooper 2010, Ley-Cooper & Quintanar-Guadarrama 2010, Ward & Phillips 2010), refer to a set of principles and criteria used as a standard for the certification programmes. These can be either voluntarily and/or independently evaluated by a third party MSC) (Marine Stewardship Council 2010, Ward & Phillips 2013). In the case of the MSC, principles and criteria are fairly inclusive and are based upon: a) The maintenance and re-establishment of the population of targeted species; b) The maintenance of the integrity of ecosystems; c) The development and maintenance of effective fishery management systems, taking into account all relevant biological, technological, economic, social, environmental and commercial aspects; and d) Compliance with relevant local and national local laws and standards as well as international understandings and agreements (Marine Stewardship Council 2010). Although lacking socio economic components (Liu 2010, Ward & Phillips 2013), the MSC's principles and criteria comprise a fairly comprehensive approach for addressing sustainability aspects of fisheries (Bellchambers et al. 2014). This has helped provide a logical structure and approach to this literature review section, and also to the structure of the discussion of this thesis (Chapter 9).

In our case study, the Sian Ka'an and Banco Chinchorro lobster fisheries have set an optimum scenario for assessing the effectiveness and impact of existing management

arrangements and conservation strategies, which include the establishment of both Biosphere Reserves/MPA's and the implementation of two ecolabelling initiatives (MSC and Chakay), in a highly valued fishery in the Mexican-MBRS. The effects impacts and conclusions drawn from this scientific research and five year monitoring of the populations subject to fishing, makes possible a review and evaluation of the sustainability of the *P. argus* fishery considering several angles including the ecological, environmental, social and economic aspects. This study has assessed the current situation from these perspectives in both SK and BC fisheries, subsequently providing recommendations for the stakeholders involved in harvesting and management. Recommendations derived from the results of this study will provide us with new ideas for research, and a means for assessing the effectiveness of management as well as providing strategies for improving fishing practices that offer improved sustainability for these highly valued lobster populations.

We have limited our description of characteristics of this species because existing literature on *P. argus* lobsters is extensive and diverse in terms of the biological and ecological aspects. However, this review outlines the overall material covered in this thesis, while emphasizing certain aspects which will be dealt with more thoroughly in other sections. We focus on the characteristics of fisheries in the Banco Chinchorro and Sian Ka'an Biosphere Reserves in the South-eastern Mexican Caribbean, within the Mesoamerican Barrier Reef.

1.2 Description of Study Areas:

Found within the Yucatan Peninsula in the Mexican Caribbean, towards the central area of the State of Quintana Roo, is the Sian Ka'an Biosphere Reserve (SK), which consists of 528,000 ha comprised of tropical forests, marshes and coastal lagoons (see Figure 1-1). Further south is the Banco Chinchorro Reserve (BC) comprising 144,360 ha including reefs, lagoons, some keys and adjacent oceanic waters (Figure 1-1 and Figure 1-2). Both are considered areas of high bio-diversity and recognized as important biogeographical components of the Mesoamerican Barrier Reef System (MBRS). This is the second largest reef system in the world stretching 720 km from Mexico to Honduras (Seijo 2007), and contains more than 50 species of corals, 400 species of fish, 30 species of sea fans, several species of seagrass, algae and mangroves, in this complex underwater ecosystem (Seijo 2007, Muhling et al. 2013).



Figure 1-1 Regional Map showing Mexico bordering the United States of America (U.S.A) to the North and Central America (Belize and Guatemala) to the South East, also the location of the Caribbean Sea and the Mesoamerican Barrier Reef System (MBRS). The Blown up image shown in the green rectangle shows the South coast of the state of Quintana Roo which forms part of the Yucatan Peninsula, surrounded by the Gulf of Mexico to the North and the Mexican Caribbean to the east. The red rectangles surround the two Biosphere Reserves of Sian Ka'an (SK)-North and Banco Chinchorro (BC)-South; the area where this study is based.

1.2.1 Banco Chinchorro:

Banco Chinchorro BC is located off the southeast coast of the Yucatan Peninsula, Mexico (see Figure 1-1 and Figure 1-2), near the border with Belize, and was declared a Biosphere Reserve in 1996 (López & Consejo 1986 , INE-SEMARNAP 2000). It is an oval-shaped atoll-like reef with a surface area of 700 km² (18°47'–18°23'N, 87°14'–87°27'W), where the longest axis measures 43 km and the shortest axis is 18 km. It is separated from the coast by a distance of 30.8 km from the nearest port (Mahahual) and by a channel ~1000 m in depth (Beltrán-Torres et al. 2003, González et al. 2003, Borges-Souza 2011).

Banco Chinchorro forms a complex system of coral patches and ridges encompassing a reef lagoon. It has up to 14% hard coral coverage at some sites (Figure 1-3), significantly higher than the average of 8% estimated for the Caribbean Sea (Chávez et al. 1985, Jordán & Martín 1987). Beltrán-Torres et al. (2003) described a patch in BC where five species with higher importance values (>25%), in descending order, were: *Porites astreoides* (84.8%), *Agaricia agaricites* (62.0%), *Madracis decactis* (27.2%), *Porites porites* (26.3%) and *Favia fragum* (25.7%).

The distance from the coast and its status as a protected area have minimized the impact of coastal development on the ecosystems (Chávez et al. 1985, Jordán & Martín 1987, INE-SEMARNAP 2000, Borges-Souza 2011, Contreras-Silva et al. 2012) yet the recent impacts of hurricanes have had effects upon the ecosystem (Beltrán-Torres et al. 2003, Ley-Cooper 2013).

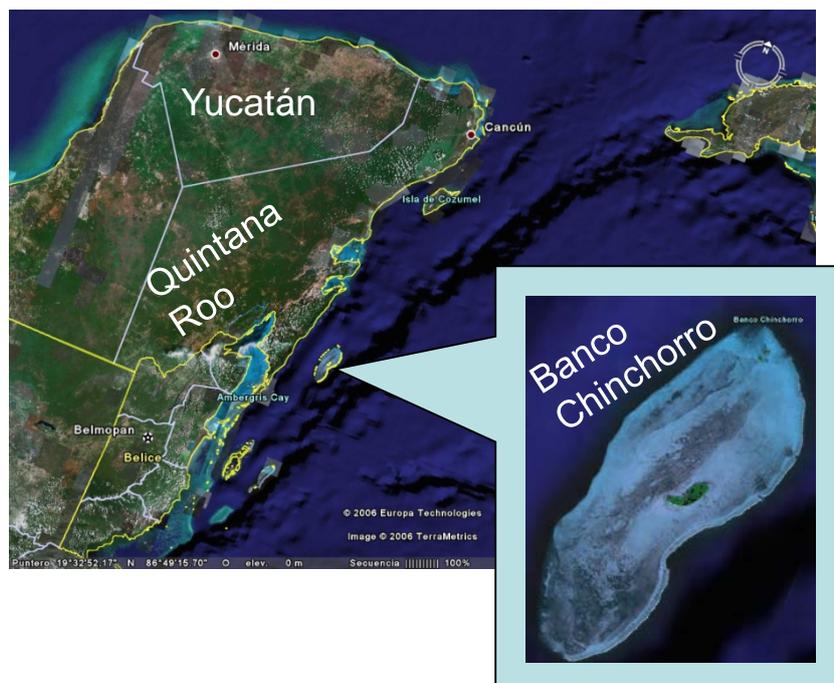
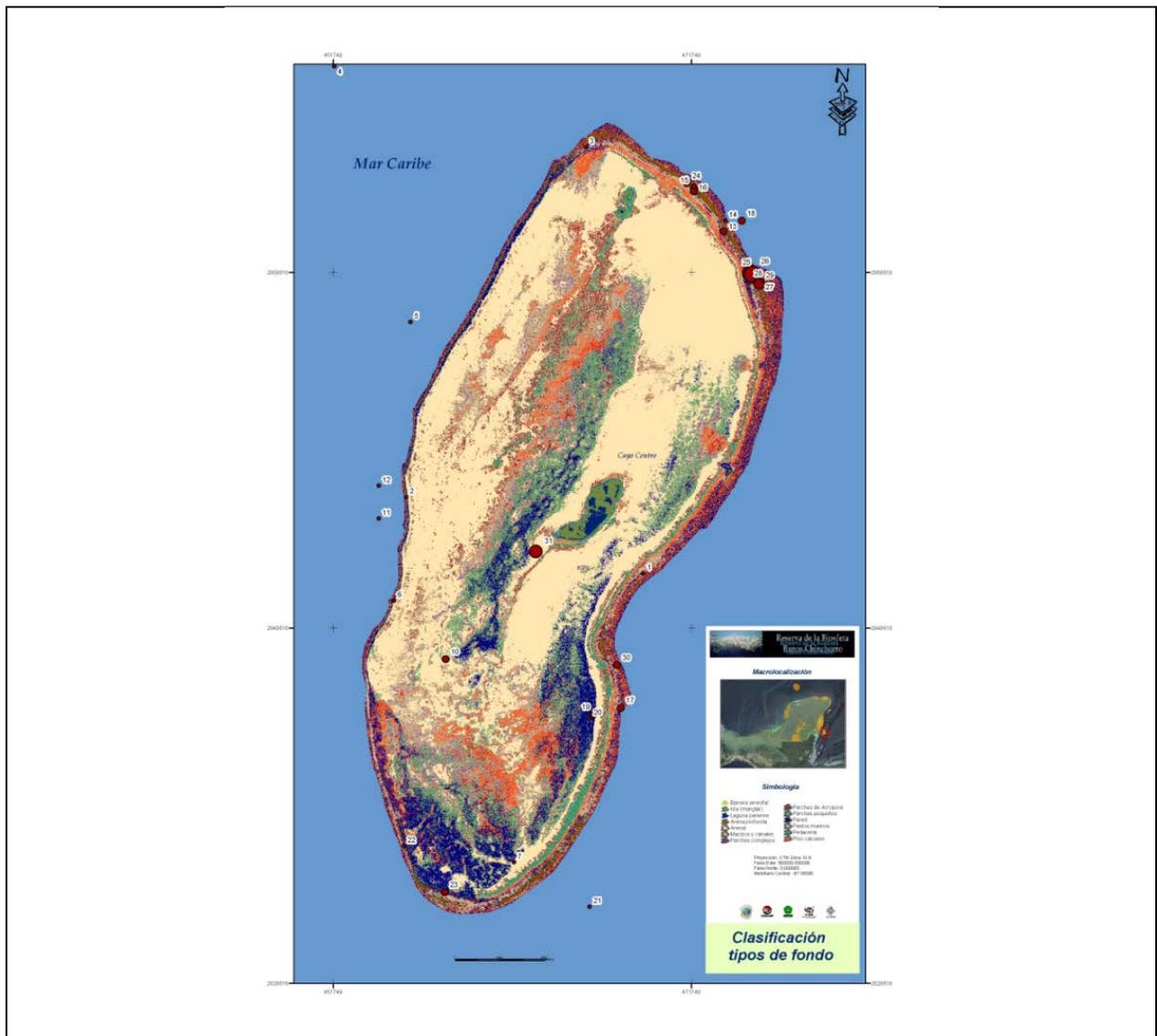


Figure 1-2 Map Showing a blow up image of Banco Chinchorro Biosphere Reserve within the regional context found to the south of the state of Quintana Roo in the Yucatan peninsula Mexico.



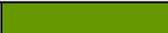
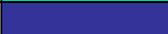
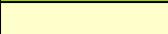
| Enlargement and translation of the habitat categories and colours of the map above. | | | |
|---|---|-----------------------|---|
| islands/mangroves |  | deep sand |  |
| complex patches |  | broken reef |  |
| small reef patches |  | barrier reef |  |
| lagoon |  | sand banks |  |
| seagrass |  | reef walls |  |
| <i>Acropora</i> reef patches |  | calcareous floor-beds |  |
| channels and reef patches |  | |  |

Figure 1-3: Shows satellite image of the Banco Chinchorro Atoll, illustrating the distinct habitats depicted in different colours (shown in the inserted table). The original habitat map was produced by Arias et al. in a CINVESTAV/CONANP-BC project 2005. It was then after modified by Ley-Cooper (2006), to include a series of *P. argus* observation sites represented by the red circles. The relative size of the red circles, and the numbers beside these correspond to density measurements (# lobsters per hectare), which were determined by diving observation transects.

The following figure was produced relatively recently by Borges-Souza (2011), as the result of a comprehensive study which included diver based video and photo transects at the site, and offer a general ecological framework of the BC area, as well as satellite/GIS image analysis. Detailed description of methods can be found in (Borges-Souza 2011), but in general terms photographic samples were taken at depths ranging from 1 to 35 m. The photographic samples were analysed using the Coral Point-Count with Excel (CPE) method and data were processed with the aid of current multivariate statistical procedures, to determine dominance and patterns of coral community structure by area (Figure 1-4). Satellite images of BC were examined to identify and evaluate the main topographic trends, and ten different habitats were identified with the aid of a GIS. General results of the Borges-Souza (2011) were:

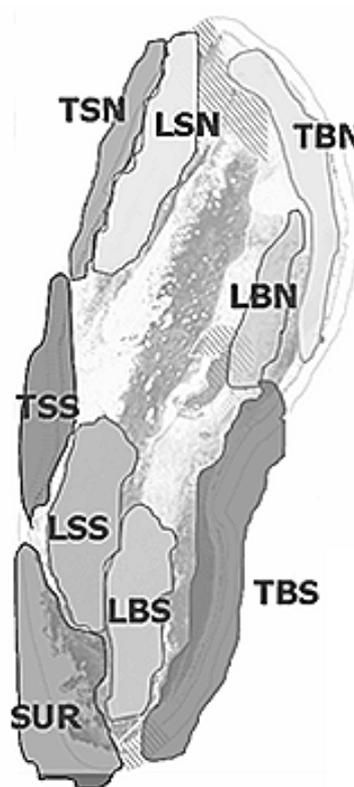


Figure 1-4 From Borges-Souza (2011), with coral community habitats, defined by cluster analysis of photographic samples (right). Nine reef types were identified TBS (Talud barlovento sur), LBS (Laguna barlovento sur), TSS (Talud sotavento sur), LSN (Laguna sotavento norte), LSS (Laguna sotavento sur), SUR (Punta sur), TBN (Talud barlovento norte), TSN (Talud sotavento norte), LBN (Laguna barlovento norte) plus 534km² of sandy bottom/ refuge-lacking “bare” lagoon with gravel, and seagrass are shown in pale grey. Significant differences in coral species richness were found between these areas.

The reef: has irregular elliptical shape, and the reef lagoon of about 547 km², is shallower (~2-5 m) in the northern half, becoming deeper (~ 5-13 m) in the south, and is completely surrounded by a reef rim 115 km long (Figure 1-4).

The coral community: Identification of nine groups of the coral community. In these areas, 159 species from 4 taxonomic groups (hexacorals, octocorals, sponges and algae) were recorded and dominant species on the reef consist of *Montastraea annularis*, *Agaricia agaricites*, *Siderastrea siderea*, *Dictyota dichotoma*, and *Halimeda opuntia*.

Species richness: The highest species number was found in the southern reef lagoon, with 78 species. By depth, the highest species richness was found between 10 and 20 m. Differences were significant between shallow and deep reef slopes. The greatest species richness was found in the northern lagoon with 68 species. When the community structure possibly driven by wave intensity was compared, significant differences were found between the northern and southern lagoon, and between the leeward reef and the windward reef.

The study of Borges-Souza (2011) concluded that the structure of the coral community has remained stable for a long time, with attributes similar to those observed at present. Species records in photographic samples were carried out at 31 random points, where the species were identified, yet the study considered that with the use of more than 15 points, at least 70 % of benthic species were represented, with a 95% confidence limit.

Habitat conformation in BC has also been studied by applying remote sensing methods to the pre-processing of satellite images in order to identify submerged aquatic ecosystems (Contreras-Silva et al. 2012). Considering the visual comparison with categories identified by previous studies such as those by (Aguilar-Perera & Aguilar-Dávila 1993) Chávez and Hidalgo (1984) and Jordán (1979) and the consistency with the theory of the zonation of benthic bottoms based on depth, Contreras-Silva et al. (2012) concluded that the classifications obtained by ISODATA successfully determined the majority of benthonic cases defined in their study of BC, and presented the following Figure 1-5:

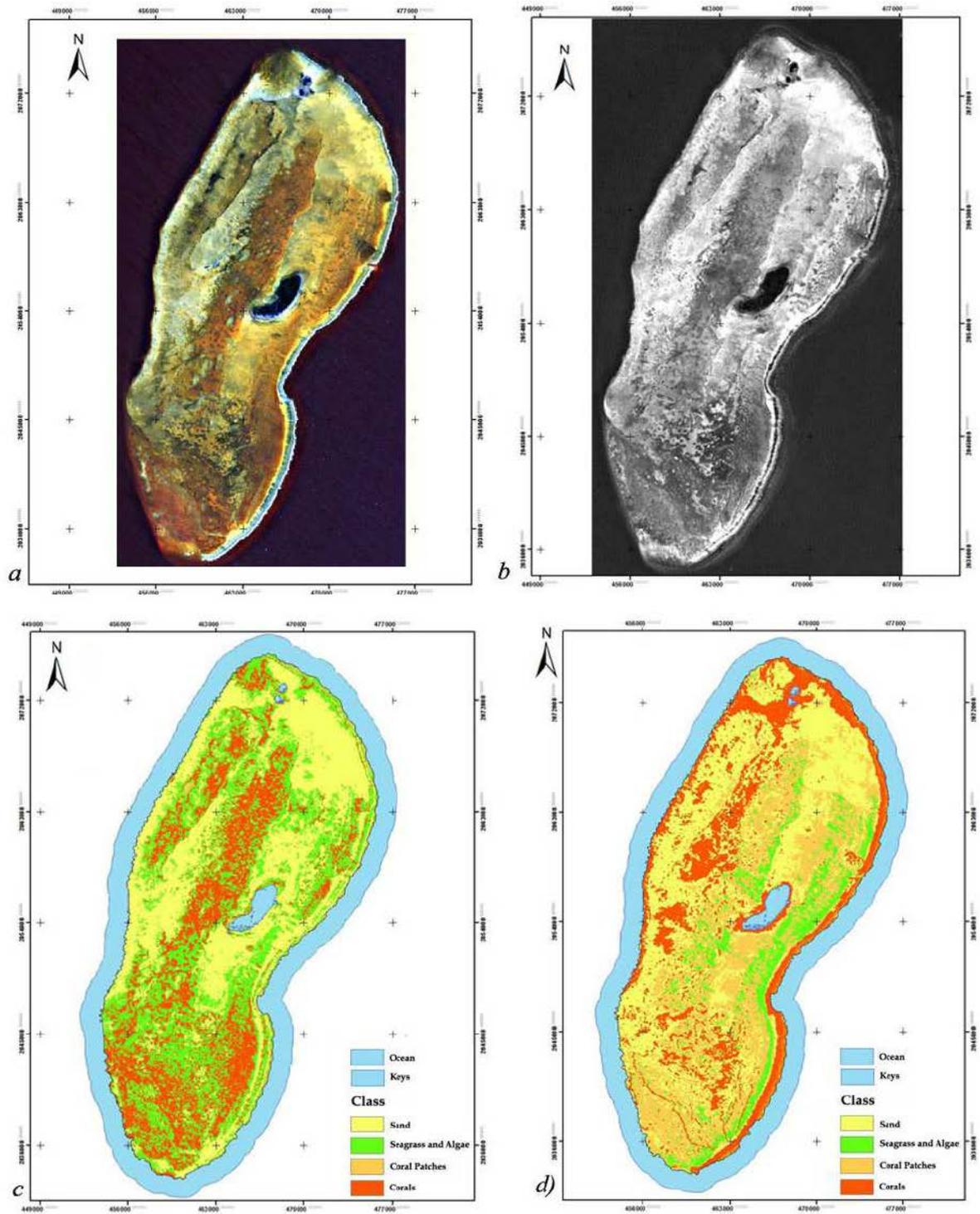


Figure 1-5 From Contreras-Silva et al. (2012) a) Landsat 7-ETM+ image, RGB (1, 2, 3), b) image resulting from the depth-invariant index by bottom type using bands 1 and 2, and classification of the benthic bottom in the Banco Chinchorro using ISODATA, c) without water column correction and d) with water column correction.

In the study by Contreras-Silva et al. (2012) ISODATA was used as a classification method of the submerged benthic ecosystems in BC based on data from Carricart-Ganivet et al. (2002), where 4 of the most representative classes were determined: 1) coral mass, 2) coral patches, 3) seagrass and algae and 4) sand. Their results were visually evaluated according to the quality of the segmentation using the classification by Aguilar-Perera and Aguilar-Dávila (1993), and bathymetric data, that greatly determine the ecology of the corals. As explained by Contreras-Silva et al. (2012) Figure 1-5a shows the Landsat image with atmospheric correction for the RGB (1,2,3) combination and Figure 1-5b shows the image resulting from the depth-invariant index by bottom type. At the bottom of Figure 1-5, two images classified using ISODATA are included, both with the same type and number of classes. Figure 1-5c presents the classification performed without water column correction; that is, using the image from Figure 1-5a as input. Figure 1-5d includes the classification performed based on the depth-invariant index (shown in Figure 1-5b); that is, taking into account water column correction.

To identify the categories resulting from the ISODATA process, Contreras-Silva et al. (2012) mentions that in (Figure 1-5c) the classification without water column correction produced a substantial mix of classes throughout the image, unlike the classification obtained by applying water column correction (Figure 1-5d). According to authors such as Aguilar-Perera and Aguilar-Dávila (1993), Chávez and Hidalgo (1984) and Jordán (1979), the periphery of BC is surrounded by abundant coral growth on the eastern margin. A barrier reef is thereby formed that disappears along the western margin where the coral growth is semi-continuous and diffuse. This spatial distribution of the corals can be clearly seen in the results of the classification with water column correction (Figure 1-5d), unlike classification without correction (Figure 1-5c).

Contreras-Silva et al. (2012) also mentions that the shallower zones are located in the northern (1-2m) and central (3 and 4 m) portions; these two zones best correspond to the zone with seagrass generated in the image shown in Figure 1-5d, as opposed to the image in Figure 1-5c where it can be seen that the seagrass class is distributed throughout the bank. In addition, Figure 1-5c shows a mix between seagrass and corals, a result that is not justifiable since the corals normally develop at depths between 5 and 30m. Using the depth criterion again in order to define the zonation, Contreras-Silva et al. (2012) state that the classification with water column correction produces good results for identifying coral patches, since they are found at depths between 7 and 12 m, as can be seen in Figure 1-5d. As a general

observation, Contreras-Silva et al. (2012) state that the results of the classification with water column correction generate data that are consistent with the theory regarding the influence of depth in defining the zonation of benthic bottoms, as well as observation of other authors regarding the spatial distribution of sea-bottoms.

The study by Contreras-Silva et al. (2012), acknowledged the need to incorporate statistical validation to data, so as to determine the accuracy of applied classifications when these are compared to field observations. Although their classification apparently resulted in visually optimal results, the latter was not possible because an adequate database of *in situ* sampling was not made available. Ground truthing of habitat identification is a necessary process for interpreting and validating images produced by satellite or any remote sensing technology, especially if these may be considered for addressing environmental changes or considerations regarding habitat impact by fisheries (Bellchambers et al. 2014). Developing and applying a long term monitoring program to create an adequate database of *in situ* sampling would be recommendable, in order to assess possible changes in the ecosystem and habitat in BC or SK (Bellchambers et al. 2009).

1.2.2 Sian Ka'an-SK:

The Sian Ka'an Biosphere Reserve (SK) is situated to the South-east of the State of Quintana Roo in the Yucatan Peninsula, facing the Mexican Caribbean coast north from BC, 50 km to the north of Chetumal city and 130 km to the south of Cancún city (See Figure 1-6). The SK Biosphere Reserve has a total surface area of 528,000ha: 408,000 ha is terrestrial and 120,000 ha marine where the two bays of Bahía de la Ascensión (BA) and Bahía del Espíritu Santo (BES) are located (see Figure 1-6). These Bays contain two of Quintana Roo's State most important lobster fishing grounds, with fisher camping grounds at Punta Allen, Marielena, and Punta Herrero (Lozano-Álvarez et al. 1991b, Lozano-Álvarez et al. 1993, CONAPESCA-SAGARPA 2013, Ley-Cooper et al. 2014).

As described in INE-SEMARNAP (1996) the Sian Ka'an Biosphere Reserve has delimited three marine coastal preservation areas called "Zonas Núcleo Marinas". These include the Federal Marine Terrestrial Zones (sand and dunes bordering water limits), reef lagoons, reef crests, and the frontal reef reaching the deepest limits established by the eastern border of the Reserve, and are enlisted below:

- The Northern zone: "Xamach", which ranges from Punta Yuyum up to Punta Xamach. The northern limits are in the coordinates: 19° 59'39 N, 87° 27'52 W and

the southern limit in the coordinates 19°55'45 N, 87°26'16 W up to the eastern limit of the Reserve.

- The Central Zone “Moox Kanab Ogi”, which includes Punta Arena, Punta Piedra, Punta Estrella and Punta Loría. The northern limit is in the coordinates 19°34'00 N-87°24'52W, up to the eastern limits of the Reserve, and the southern limit 19°31'00N-87°25'50 W up to the eastern limits of the Reserve
- The Southern Zone “Tantaman” with northern coordinates of 19°16'00 N-87°29'05 W and southern coordinates 19°13'00 N-87°32'03 W up to the eastern limits of the Reserve.

As described in CONANP (2007); Sian Ka'an lies on a partially emerged coastal limestone plain, which also forms part of the extensive 720 km MBRS (Seijo 2007). Over half the area, as far as 40 km inland consists of salt and freshwater marshland in the catchments of the wide bays, 20% is semi-evergreen forest on slightly higher ground; 23% is reef and marine. The 120 km coastline includes white sandy beaches, extensive mangrove stands and creeks, and shallow bays covering over 100,000 ha, with varying salinity and dotted with islets and mangrove keys. There are 137 islands within the site. The floor of the bays is either sand or covered by sea grass. Coastal marshes and mangroves are largely protected from the sea by a 110 kilometre-long 15000 ha stretch of the barrier reef, which became established partly due to the lack of land erosion, resulting in silt-free water. The boundaries coincide with natural features: the sea and barrier reef to a depth of 50 m in the east.

Annual sea surface temperature (SST) in SK ranges between 24.4 to 32.2 °C, with periods of low temperature occurring between the months of October and March, which are commonly associated with the passage of Nortes (Briones-Fourzán 1994). Nortes begin to affect BA in autumn, mainly during October and November (Briones-Fourzán 1994) and are easily detected because of their marked sudden increase in wind speed which changes direction to come from the north. Nortes are also preceded by a calm or short windless period (≤ 24 hours) after which wind direction changes abruptly. They generally last between two and five days (Merino and Otero 1991).

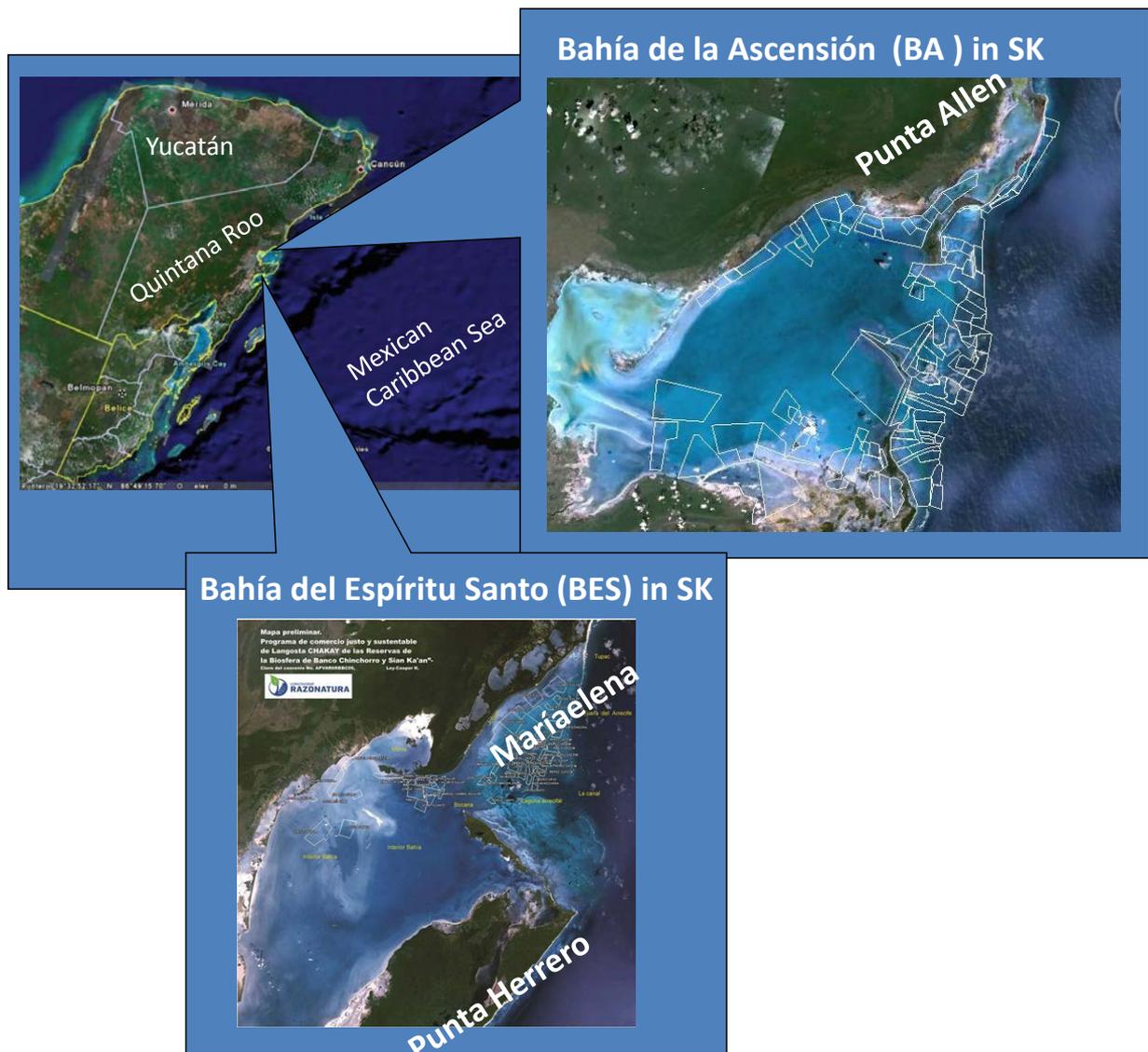


Figure 1-6 Map Showing a blown up image of Bahía de la Ascensión (BA) and Bahía del Espíritu Santo (BES) in the Sian Ka'an Biosphere Reserve (SK) within the regional context found to the southeast of the State of Quintana Roo in the Yucatan peninsula Mexico.

1.2.2.1.1 Bahía de la Ascensión (BA)-Punta Allen in North SK

Bahía de la Ascensión (BA) is the northern bay of SK. BA is a large (~740 km²) and shallow (<6 m deep) bay, bordered by mangrove and grass swamps, with a substantial part of the bottom covered with seagrass (mainly *Thalassia testudinum*) and dense aggregations of red and green algae. A coral reef tract runs parallel to the mouth of the bay, protecting the inner waters of the bay from wave surge (Lozano-Alvarez et al. 1993). Seagrass, mangroves, and coral reef patches comprise favourable habitats for settlement and growth of *P. argus* (Briones-Fourzán et al. 2000; Sosa-Cordero et al. 2008). Due to the karstic landscape, BA has a large drainage basin and hence behaves as an estuary with an intense water exchange across

the bay's inlets along its mouth (Medina-Gómez et al. in press (Medina-Gómez et al. in press)).

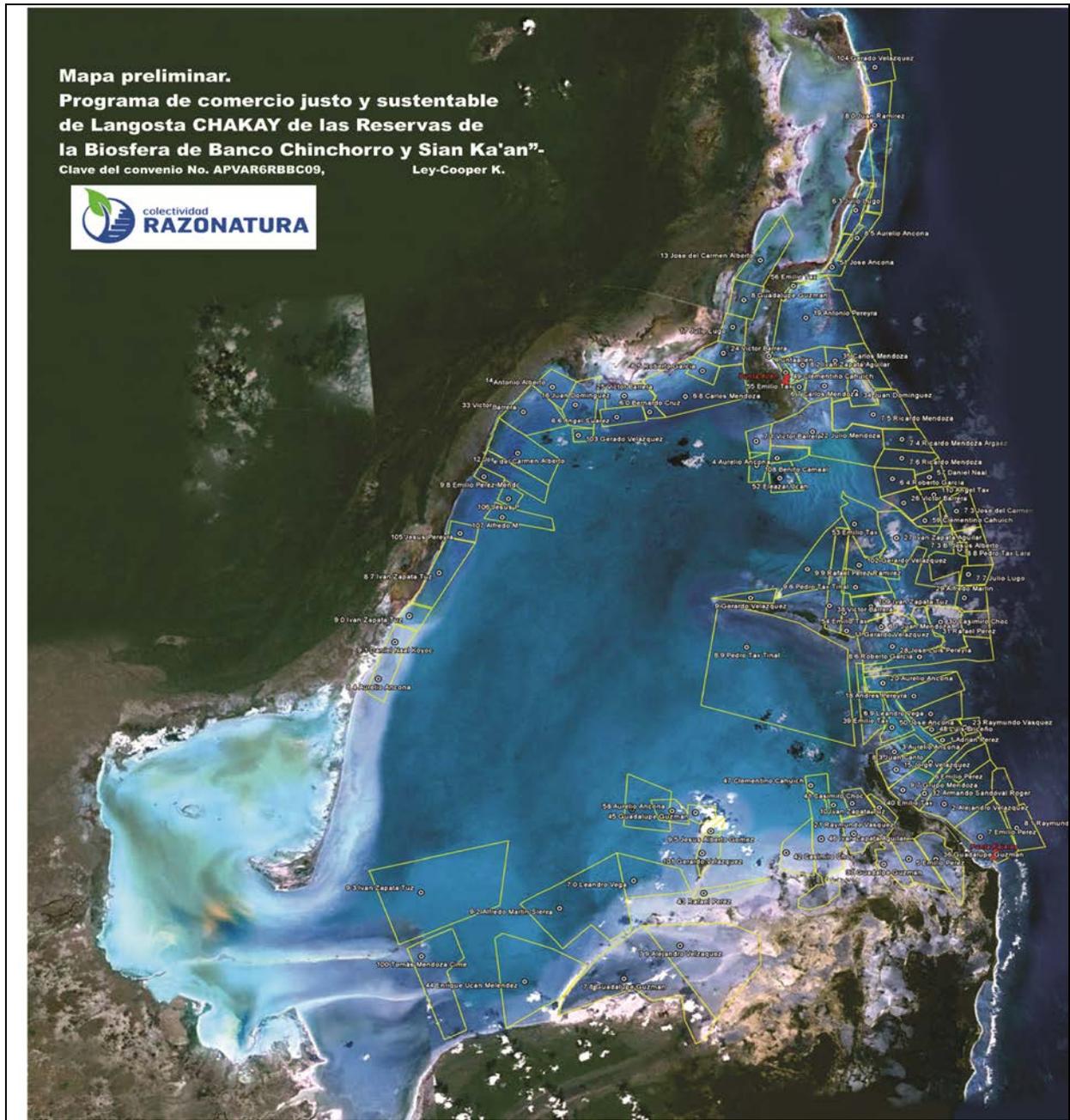


Figure 1-7 Map showing the campo plots within Bahía de la Ascensión BA from Ley-Cooper (2009), the northern bay of the Sian Ka'an Biosphere Reserve *P. argus* lobster fishery. Areas are under concession to the cooperative Vigía Chico.

1.2.2.1.2 Bay of Espíritu Santo (BES) in South SK

Most of the sections in this thesis relating to tagging were conducted in the southcentral segment of the SK coast in Bahía del Espíritu Santo (BES) (See Figure 1-6). Here, the continental shelf is narrow, not exceeding four km from the coast and ending at

depths averaging 50 to 60 m, after which depths rapidly reach >400 m (Lozano-Álvarez et al. (1991a). Bahía del Espíritu Santo is a large and shallow bay ranging in depth from 1-20 m, with an area of approximately 300 km² (Sosa-Cordero et al. 1999). Within this bay there is a *P. argus* lobster fishery with limited access, co-managed by environmental and fishery federal government authorities (Sosa-Cordero et al, 2008, (Ríos-Lara et al. 2012), exclusively exploited by two cooperatives i) SCPP Cozumel in the northern segment of BES (Figure 1-8) based in the camp site of Marielena (Figure 1-6) and ii) José María Azcorra in the southern segment (Figure 1-9) based in the camp site of Punta Herrero (Figure 1-6) (Ley-Cooper et al. 2013).



Figure 1-8 Map showing the Campo plots within Bahía del Espíritu Santo (BES) from Ley-Cooper (2009), the southern bay of the Sian Ka'an Biosphere Reserve (SK) *P. argus* lobster fishery. Areas in the northern portion of the bay are in concession to the cooperative Cozumel, with a fishing village in Marielena and a landing site at Punta Herrero.

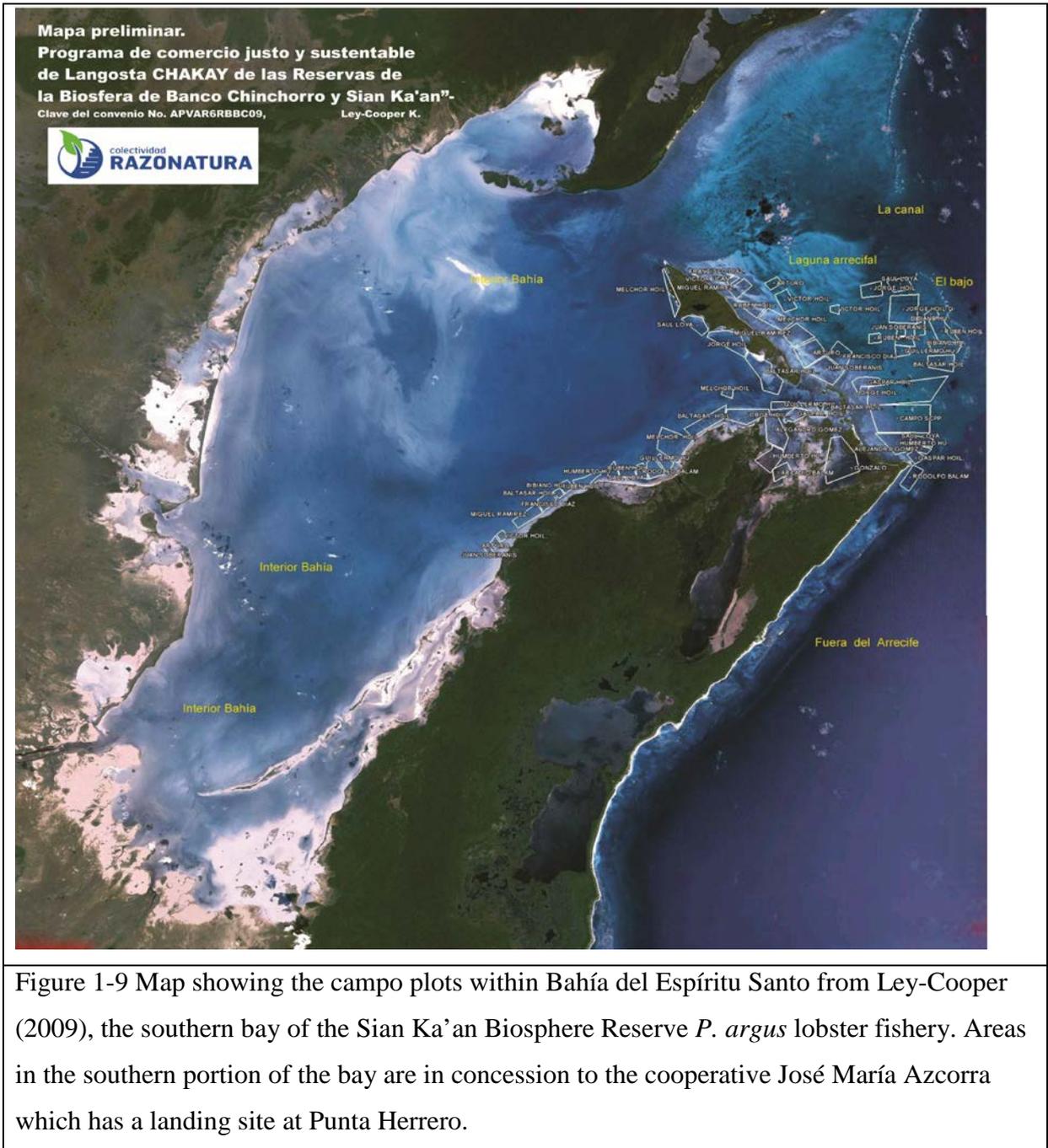


Figure 1-9 Map showing the campo plots within Bahía del Espíritu Santo from Ley-Cooper (2009), the southern bay of the Sian Ka'an Biosphere Reserve *P. argus* lobster fishery. Areas in the southern portion of the bay are in concession to the cooperative José María Azcorra which has a landing site at Punta Herrero.

1.3 Taxonomy and systematics of *Panulirus argus* (Latreille, 1804)

| Kingdom | Phylum /division | Class | Order | Family | Genera | Species |
|----------|---------------------|--------------|----------|-------------|------------------|----------------------------|
| Animalia | Artropoda | Malacostraca | Decapoda | Palinuridae | <i>Panulirus</i> | <i>Panulirus argus</i> |

The terms spiny lobster and rock lobster refer to some 40 species of clawless lobsters from the Palinuridae Family (Phillips 2006, Phillips 2013, Phillips et al. 2013). Lipcius and Eggleston (2000) studied the systematics, evolution and morphology of the more than 20 species of *Panulirus* found in the tropical and subtropical waters of the worlds' oceans, which is very detailed. The common name for *Panulirus argus* is Caribbean Spiny Lobster and will be referred to as *P. argus* henceforth in this thesis. This is a decapod crustacean classified in the Palinuridae family, which includes nineteen species of the widely distributed and intensively fished genus *Panulirus* (Lavalli & Spanier 2010, Naro-Maciel et al. 2011, Briones-Fourzán & Lozano-Álvarez 2013).

The *P. argus* lobster is a tropical and subtropical species found in Western Atlantic Ocean from North Carolina-USA to Brazil, as well as Bermuda, Bahamas, and West Indies, with the greatest stocks located in the larger continental shelves of the region in Brazil, Honduras, Nicaragua, Florida, Bahamas and Cuba, and significant fisheries in the MBRS including Belize and Mexico (see Figure 1-10) (Herrnkind 1980, Lipcius & Eggleston 2000, Ehrhardt et al. 2010b). The wide distribution of this species is attributed partially to the long distances travelled during larval dispersal combined with a capacity to adapt to various habitats. Many studies have been carried out to investigate the source of the larvae, postlarval settlement, recruitment and dispersal patterns, the influence of physical factors upon these, and the possible sources of origin (Briones-Fourzán et al. 2008, Butler et al. 2008, Butler et al. 2011, Naro-Maciel et al. 2011, Briones-Fourzán & Lozano-Álvarez 2013, Truelove et al. 2014).

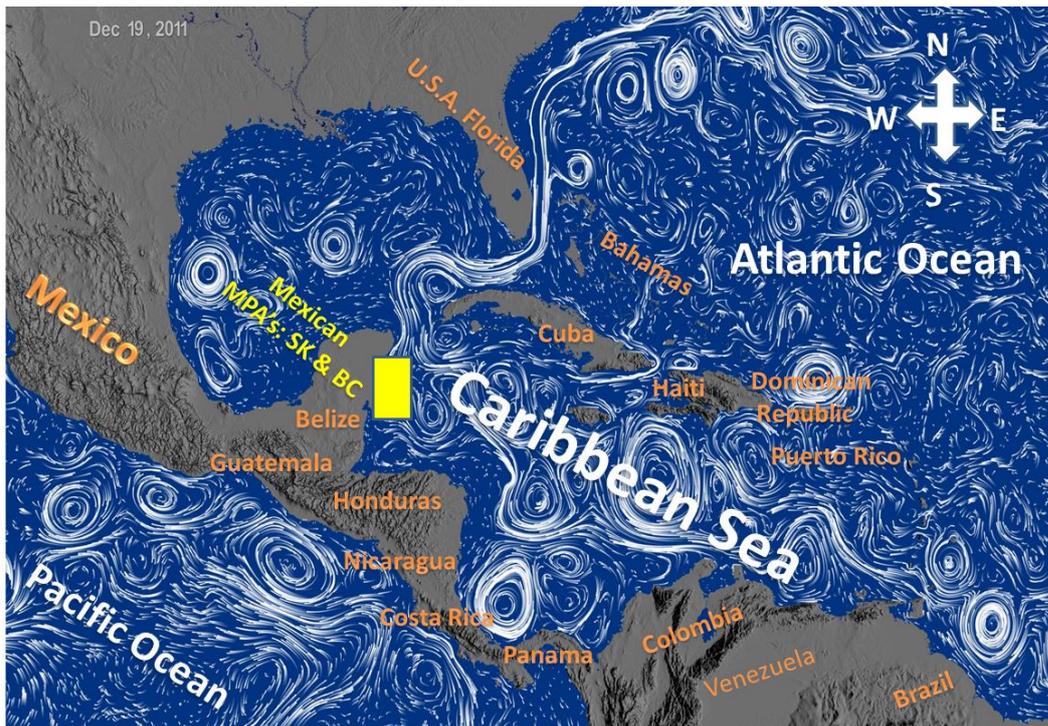


Figure 1-10 Map showing the Caribbean Sea in blue and main current trends in white (Courtesy of NASA/GSFC Scientific Visualization Studio from Truelove (2014)), the original has been modified to include important reference labels and names for areas of the Caribbean Sea, in order to identify the region where lobster species *P. argus* are distributed.

1.3.1 Phylogenetics of *Panulirus argus*

Lobster phylogenetics and population genetics among *P. argus* are evolving as an important field of study (see section 1.5) (Truelove et al. 2011, Truelove 2014, Truelove et al. 2014, Truelove et al. 2015), as molecular tools are increasingly applied to extant taxa in order to compare taxonomies on the basis of morphological distinctions. As a result new phylogenetic hypotheses have emerged that examine relationships not only between the taxa of a family, but also the relationships between the families of Palinura (Lavalli & Spanier 2010). Characteristic colour patterns distinguish Brazilian spiny lobster *P. argus* from populations in the western Atlantic and Caribbean, and comparison has indicated variation in two mitochondrial genes (Silberman et al. 1994, Sarver et al. 1998). Sarver et al. (1998) carried out a Phylogenetic analysis of 16S sequence data revealed two distinct clades of *P. argus*, a clade that comprises Caribbean populations and a second clade of samples comprising those from Brazil. Mean sequence divergence between these two was 8.32% for the mitochondrial large subunit ribosomal RNA (16S) and 19.82% for cytochrome oxidase I

subunit (COI). These indicators of degree of differentiation between clades formally concede two sub species of *P. argus*, resulting in authors dealing separately with the two species (Sarver et al. 1998). However studies carried out by Naro-Maciel et al. (2011) produced further insights into the unknown history of *P. argus*, and investigated population structure by using high-resolution mitochondrial DNA from controlled regional sequences.

Analysis from two divergent lineages within the Caribbean, (*P. argus* and *P. argus westonii*) (Sarver et al. 1998) had suggested that northern Caribbean groups such as Florida might be distinct from southern area groups including Puerto Rico, thus to be considered as a separate subspecies (Diniz et al. 2005). Regional structuring was proposed as the reason that *P. argus* in Brazil was considered genetically divergent from and also a different colour to *P. argus* (Diniz et al. 2005). Mitochondrial comparative analysis of genetic variation revealed similar average intraspecific divergence levels amongst several *Panulirus* species, yet substantiated the hypothesis of panmixia throughout this region (Naro-Maciel et al. 2011). Likewise, Naro-Maciel et al. (2011) reported that their results were consistent with regional biophysical dispersal models (Briones-Fourzán et al. 2008, Butler et al. 2008), and confirmed a high degree of connectivity indicating that larval sources may be distant from eventual post-larval recruitment sites (Naro-Maciel et al. 2011), indicating the need for regional management of this shared resource (Butler et al. 2008, Ehrhardt et al. 2010a). The literature concerning speciation within Caribbean *P. argus*, suggested further research is required to more definitely indicate whether these lineages are reproductively isolated and whether they represent cryptic species. This would also improve understanding of population structure and provide new insights into species identification and population history of *P. argus* (Naro-Maciel et al. 2011). Thus it is important to carry out further population genetic analysis, which formed part of the collaborative work undertaken throughout this thesis project and presented in section 1.5. (Truelove et al. 2011, Truelove et al. 2014, Truelove et al. 2015)

1.4 Biological aspects of *Panulirus argus*

Effective species management can be greatly enhanced by a thorough understanding of biology. Many publications relate the biology of spiny lobster (see Lipcius and Eggleston (2000)), yet the book edited by Phillips (2013) has some of the most updated information specifically in sections authored by Briones-Fourzán and Lozano-Álvarez (2013), Groeneveld et al. (2013) and Phillips et al. (2013). We review general information found in the existing literature regarding *P. argus* species biological characteristics in this thesis and include a

summary of different aspects such as life cycle phases, growth factors, migration behaviour, population dynamics, relation to habitat, ecology and interaction with environmental factors. We have acceded to limitations imposed by the scope (see Chapter 2) and size of this thesis (100,000 words maximum), so besides this general overview, we discuss further details and specific aspects of these themes in each of the different chapters and discussion section's, within the corresponding titles and subtitles.

1.4.1 General Biology

1.4.1.1.1 Morphology

Many authors have provided complete descriptions of Palinuridae lobster morphology and reviewed general characteristics, and included information regarding the general anatomy of *P. argus* (Lipcius & Cobb. 1994). These lobsters have a striped body, brown-yellow and reddish-orange in colour (depending on habitat), with yellow and black spots on the segmented tail (Saul 2004). They have compound eyes and can detect orientation, form, light, and colour. Lobsters will flick and bend their large abdominal tails and rapidly swim back to safety when touched or disturbed.

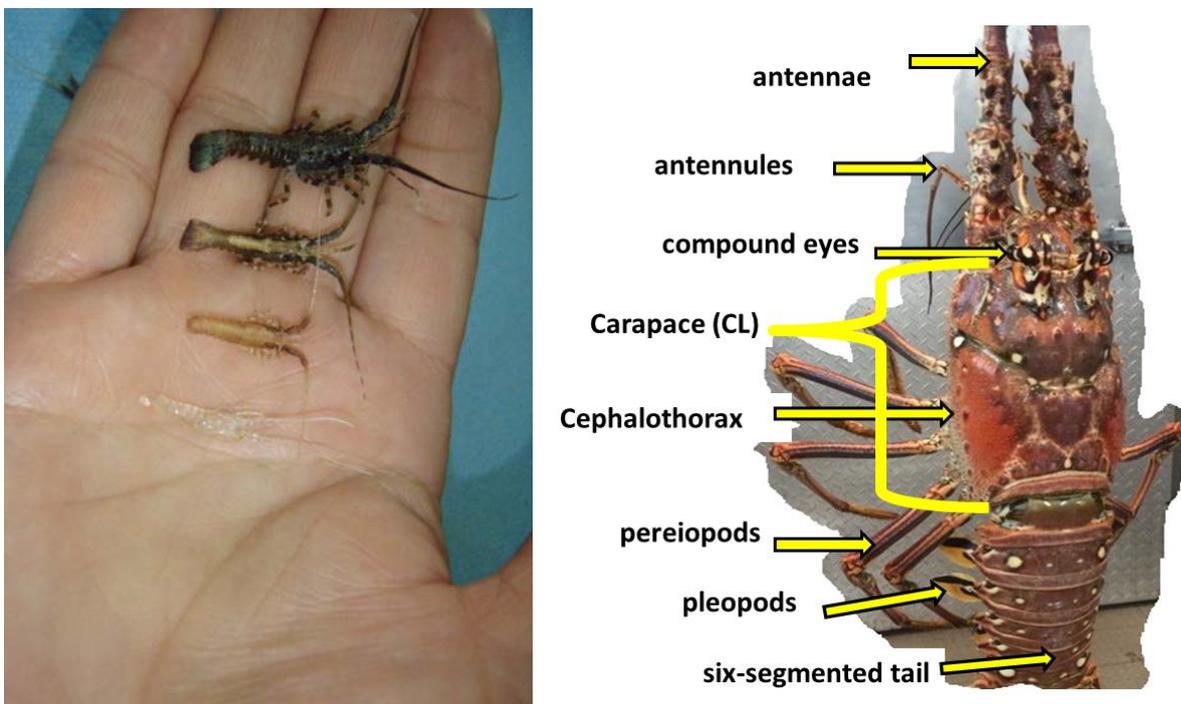


Photo 1-1: by Kim Ley-Cooper i) Right photo showing a large (> 12 cm carapace length (CL)) adult male *P. argus* lobster caught in BC. Yellow arrows indicate the different segments that constitute the body; and ii) left photo shows a hand holding four individual *P. argus* lobsters in different development phases (pueruli and juvenile), showing consecutive

morphological stages: a) at the bottom transparent puerulus (post-larval), b is pigmented puerli with two different colouring and size; c) benthic “algal” juveniles with approximately 2 moults; and d) benthic “algal” juveniles with approximately 4 moults respectively.

Spiny lobsters present sexual dimorphism and males reach larger lengths and weights than females. Global population samples show that there is a 1:1 sexual ratio; however, this varies with time and depths, most probably as they move between habitats as they search for refuge, food and to reproduce (Briones-Fourzán et al. 1997, Bertelsen 2013).

The anatomy of *P. argus* conforms to the typical decapod body plan consisting of five cephalic and eight thoracic segments fused together to form the cephalothorax (see Photo 1-1). The carapace, a hard shield-like structure, protects this portion of the body and the part of the lobster usually measured and regarded as a standard to determine organism length (Saul 2004). In *P. argus* all the segments bear paired appendages for locomotion or sensory purposes, or both. Lobster, appendages initiate from the head and follow in order with the first antennae, second antennae, mandibles, first maxillae, and second maxillae. There are five pairs of legs for walking known as pereopods and a six-segmented tail. All palinurid spiny lobsters use a first pair of antennae (the antennules) for sensory perception. The antennules primarily obtain sensory information by chemoreception, as do the dactyls of the legs and the mouthparts involved in handling food. The paired, lateral compound eyes of lobsters provide great visual ability. In addition, highly distributed superficial hairs detect water movements (Lavalli & Spanier 2010).

Lavalli and Spanier (2010) comment on the extensive studies of the spiny lobster, particularly *P. argus* where an attempt is made to explain the array of chemoreceptors that are used for feeding, habitat selection, mate selection, and social and anti-predator behaviour. Chemical sensory organs are located on most surfaces, particularly on the antennules, pereopods, and mouthparts, but also on the carapace, pleon, and telson. Antennules bear hundreds of thousands of chemoreceptor neurons that are sensitive to a wide array of water-soluble molecules, where chemical signals such as pheromones may be encoded by labelled lines to assure appropriate responses (Derby et al. 2001). Similarly when in defensive rosettes, individuals that are subject to aggression will point and whip their spinose antennae (or lunge while whipping), while simultaneously producing stridulatory sounds, which possibly act as aposematic cues to predators (Bouwma & Herrnkind 2009). These sounds are also produced if individuals defect from the group (or become solitarily) and execute a tail flip when attempting to escape a predator that approaches them. Stridulation, in addition to

the defensive action (whipping, lunging, tail flipping), appears to confer an advantage to individuals; as they survive and/or escape predators more often than silent lobsters, possibly due to the vibrations this produces in the antennae (Bouwma & Herrnkind 2009).

1.4.1.1.2 Life cycle and general ecological features

As written in Phillips (1980) spiny lobsters manifest five major phases within their life cycle: adult, egg (referring to embryonic development), phyllosoma (larval), puerulus (postlarval) and juvenile. The life cycle of all *Panulirus* species includes a long oceanic larval phase, which varies in duration according to species (Herrnkind 1980, Phillips 1980). Spiny lobsters hatch as planktonic larvae (about 1-2mm long) called phyllosoma and develop through a series of moults developing distinct morphological features and increasing in size (i.e./body length (BL), Cephalic Shield length (CL): cephalic shield width (CW), Thorax width (TW) and Pleaon length (PL)) (Goldstein et al. 2006, Butler et al. 2008, Goldstein et al. 2008). The wide distribution of *P. argus* species and its capacity for dispersal has been attributed to the fact that it has a long planktonic larval phase, and spends months traveling in the open ocean partially transported by the currents (Figure 1-10 and Figure 1-11). This happens until the instars have developed sufficiently to settle as pueruli (Photo 1-1) (Briones-Fourzán et al. 2008, Butler et al. 2008, Goldstein et al. 2008, Butler et al. 2011).

The study of *P. argus* phyllosomal duration and development using laboratory cultures carried out by Goldstein et al. (2008), found that the development Stages of phyllosoma of *P. argus* are ten “X”, which are distinguished by size and morphological characteristics. The study found that the pelagic larval duration (PLD) for *P. argus* was of 6.5 months (range: 4.5-8 months), as the mean was determined to be 174 days (range 140-198 days), which were slightly shorter than estimates obtained by extrapolations from model progressions of phyllosomal stages from plankton samples (6-12 months). The number of moults for *P. argus* resulted in mean=20, (range: 18-21), and instar size mean BL=27.0mm (range 25.6-28.2mm BL). The mean body length (BL) for the newly hatched 1st instar was 1.62 mm (range: 1.56 - 1.66 mm). Then BL increased sigmoidally with development throughout the phyllosoma phase, except for the 23rd-25th instars. The duration of each instar was relatively constant (6-7 days) until the 12th instar was reached, after which instar duration increased gradually to \approx two weeks at the 19th instar.

The study with laboratory cultures also allowed Goldstein et al. (2008) to classify Pueruli (see into four groups (P1-P4), similarly to how Mc William (1995) had done based on

selected morphological characteristics including: sternal spines, apex of antennal flagellum, antenna length relative to body length and exopod condition of 2nd and 3rd maxillipeds. The BL of pueruli that metamorphosed in the individual and group cultures measured from 16.4-17.5 mm (mean = 17.0 mm) and from 15.7-17.9 mm (mean = 17.0 mm), respectively; whereas their CL measured 6.20-6.75 mm, (mean = 6.34) for individually cultured animals and 6.00-6.70 mm, (mean = 6.35) for group-cultured animals. Pueruli following metamorphosis moulted to the first juvenile instar 15-26 days after metamorphosis (mean = 22.6 days) and 16-26 days post metamorphosis (mean = 20.7 days) in individual and group cultures respectively at 25°C; while six moulted to the juvenile stage 11-18 days post metamorphosis (mean = 15.0 days) at 27°C. Pueruli used their pleopods to propel themselves forward in the vessels or stayed near the shelter during the daytime until 2-3 days after metamorphosis, after which they crawled into the shelter and became cryptic (Goldstein et al. 2006, Goldstein et al. 2008).

In oceanic waters offshore from the coastal habitats where larvae are initially released, the phyllosoma larvae grow and change as instars following the different development Stages described above (Goldstein et al. 2006, Butler et al. 2008, Goldstein et al. 2008). Near the proximity of the continental shelf is where the final stage “X” larvae metamorphose into the postlarval Stage (pueruli), a non-feeding stage that swims towards the coast (see Photo 1-1)(Butler et al. 2008, Goldstein & Butler 2009, Butler et al. 2011). When the pueruli settle they continue to moult and grow, and after a few days–weeks into the first benthic juvenile stage, with a carapace length of up to 30 mm. Small juveniles are usually found in shallow seagrass areas, algal (i.e. *Lobophora variegata*, *Laurencia* spp), hard bottom and mangrove habitats (Herrnkind & Butler 1994, Acosta & Butler 1997, Briones-Fourzán & Lozano-Álvarez 2001b, Butler et al. 2006). Lipcius and Eggleston (2000) recognize the five main phases of the life stage in *P. argus*, but have also described two or even three separate juvenile phases termed algal and post-algal for *P. argus* species, based mainly on behavioural aspects related to this benthic Stage.

During its lifetime, *P. argus* can grow from less than one gram as a Stage 1 larvae, up to five kilograms as an adult \approx 60 cm in total length (Lipcius 1986), and the long complex life cycle spreads over three distinct habitats: open ocean, shallow areas, vegetated coastal zone, and coral reefs (Briones-Fourzán et al. 1997, Jeffs et al. 2005, Goldstein & Butler 2009). *P. argus* lives as an asocial animal during its early benthic stages. Nomadic emigration from the algal nursery habitat to off shore reef habitats is reportedly a

consequence of increased aggressive interactions, as well as a decline in food availability for juvenile lobsters, which at this time live solitarily (Marx & Herrnkind 1985). *P. argus* progressively abandons the juvenile solitary behaviour and adapt to social living arrangements where they begin to share dens and refuge with other juveniles and adults, seeking protection from predators (Briones-Fourzán et al. 1997, Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2001a). As older juvenile subsequent stages of *P. argus* form social aggregations and sometimes migrate as adults from shallow to deeper waters, in search of food, shelter and responding to reproductive behaviour (Lipcius et al. 1997, Phillips 2006, Eggleston & Parsons 2008, Bertelsen 2013, Briones-Fourzán & Lozano-Álvarez 2013, Groeneveld et al. 2013, Ley-Cooper et al. 2014). Larger juveniles and adults are normally found in coastal reefs, crevices and places of refuge in deeper water; and it is in normally in the deeper reefs where they reach maturity, mate and complete their life cycles (Butler et al. 2006, Briones-Fourzán & Lozano-Álvarez 2013, Groeneveld et al. 2013).

When reaching the adult phase lobsters normally aggregate in enclosed dens and refuges, where sheltered environments may include natural holes in a reef, rocky outcrops, sponges or even artificially created refuges like casitas (see section 1.6.4.1.1) (Lozano-Álvarez et al. 1991a, Lipcius & Cobb 1994, Briones-Fourzán & Lozano-Álvarez 2013). Ontogenic and nomadic movements as well as migrations occur throughout the life cycle of *P. argus*, yet as from two years after settlement individuals manifest particularly nomadic behaviour, and emigrate from the shallows to deeper offshore reef environments for reproduction, and vice versa from the deep to the shallows in response to changes in environmental conditions (see sections 5.1, 6.1 and 7.1) (Ríos-Lara et al. 2007, Eggleston & Parsons 2008, Bertelsen 2013, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

During most of the juvenile and all adult phases *P. argus* rests in shelters during daylight hours, emerging in the evening to forage for food. *P. argus* feeds primarily on gastropods, chitons, bivalves, and carrion from the ocean floor, and is also known to feed on sea urchins, worms, crustaceans, and some types of sea vegetation. Once it emerges from the planktonic phase and enters the seagrass and macroalgae nursery habitat, diet consists of small gastropod molluscs, isopods, amphipods and ostracods, most of which can be found in or within close proximity to the algal shelter (Marx & Herrnkind 1985, Briones-Fourzán, 2003 #214{Briones-Fourzán, 2003 #214, Ríos-Lara et al. 2007). Studies suggest that as abundance of food declines in and around their algae habitat, and as lobster grow they forage more frequently and thus have more frequent contact with conspecifics (Atema & Cobb 1980, Eggleston & Lipcius 1992).

Adult lobsters are key predators in many benthic habitats with their diets consisting of slow-moving or stationary bottom-dwelling invertebrates including sea urchins, mussels, gastropods, clams and snails (Lipcius & Cobb. 1994). Large juvenile lobsters also forage at night and eat a similar diet of invertebrates, however they choose smaller sized individual prey (Briones-Fourzán et al. 2003). During feeding, they seize their prey and manoeuvre using anterior pereopods and the maxillipeds, whereas mandibles carry out mechanical digestion and are capable of crushing hard mollusc shell. Studies indicate that *P. argus* are highly selective in terms of the dens they choose to live in and crevice location and are influenced by size of dens and nearby food availability (Acosta & Robertson 2003), (Bertelsen 2013). *P. argus* night movement's away from and subsequent return to their dens illustrates the spatial orientation they have to their immediate habitats (Herrnkind 1980, Briones-Fourzán & Lozano-Álvarez 2001b, Saul 2004, Eggleston & Parsons 2008, Bertelsen 2013)

P. argus is preyed upon by many other species such as groupers, moray eels, octopus and nurse sharks, although arguably the predator with the largest impact on the species in the Yucatan Peninsula Mexico is currently the human being (Arceo et al. 1997, Ríos-Lara et al. 2007). Juveniles and adults become subject to fishing and support commercial, recreational and artisanal type fisheries throughout their geographic range (Ehrhardt 2007, Ehrhardt et al. 2010b).

1.4.1.1.3 Habitat/Reproduction and behaviour:

Table 1-1 The following is a summary of the different phases that constitute the *P. argus* life cycle, revealing several habitat shifts that take advantage of a variety of marine ecosystems during ontogenic development.

Spawning and reproduction:

Adult *P. argus* lobsters breed all year round and mainly mate in reef habitats, with peaks between March-June and a smaller peak around September-October (Briones-Fourzán et al. 1997). Reproductive females can be identified by egg mass on the underside, and/or by dark tar spot located on the ventral area of the carapace which is a spermatophore placed by the males when mating (Fonseca-Larios & Briones-Fourzán 1998, Butler & Herrnkind 2000, Butler et al. 2006);

Females bear the bright orange coloured eggs under the abdomen until these eggs change to a dark brown/black colour after an incubation period, as larvae develop and eyes become evident. Females generally move towards deeper areas to further incubate their eggs which will subsequently be released as larvae (phyllosoma) (Lipcius & Herrnkind 1987).

Larval Stage: 10 distinct Stages after hatching, s from the egg masses, the *P. argus* larval phase manifests. As phyllosoma larvae they are widely dispersed in the drift of the oceanic currents and are widely dispersed (Figure 1-10 and Figure 1-11) (Butler & Herrnkind 2000, Lipcius & Eggleston 2000),(Olsen et al. 1975, Goldstein & Butler 2009).

The larval duration of *P. argus* has been estimated to continue for 5 to 9 months prior to metamorphosis into the puerulus, which are transparent and flat (Photo 1-1), with a possible duration of up to 11 months for the northernmost range of the species (Lewis 1951 , Lyons 1980). In the laboratory, *P. argus* was raised from egg to juvenile, where metamorphosis into

the puerulus phase occurred 140–198 d after hatching (i.e., 4.7–6.6 months), with an average of 174 d (5.8 months) (Goldstein et al. 2008, Goldstein & Butler 2009). As development under laboratory conditions is usually shorter than that estimated from field sampling, a larval duration of 5–9 months for wild populations has been considered a better estimate (Briones-Fourzán et al. 2008, Phillips et al. 2013).

Variability in larval duration probably reflects individual differences in rate of development and/or a possible delay in metamorphosis resulting from nutritional constraints, as metamorphosis appears to occur in oceanic waters close to shelf breaks, dictated by the nutritional state of the phyllosoma rather than by environmental cues (McWilliam & Phillips 1997, Briones-Fourzán et al. 2008).

Larval behaviour: Phyllosomata have been reported to have limited horizontal swimming ability, but their horizontal transport may be modulated by vertical migration (Jeffs et al. 2005), as it exhibits both diel vertical migration and ontogenic vertical migration (Butler et al. 2011).

Postlarval Stage: The tenth phyllosoma Stage goes through a metamorphosis to become the pueruli, which is still transparent, but has a typical lobster shape/form, but with certain adaptations to pelagic life (Photo 1-1). Unlike phyllosoma, pueruli do not feed but are strong horizontal swimmers that swim in a particular direction near the surface across continental shelves towards coastal areas, where they settle in the offshore shallows of the backreef nursery habitat, possibly guided by underwater sound produced by waves breaking on the coastline (Jeffs et al. 2005, Goldstein & Butler 2009, Butler et al. 2011). When reaching submerged vegetative habitats at settlement stage, the size of pueruli is around 0.6 cm carapace length (CL), (Butler & Herrnkind 2000, Lipcius & Eggleston 2000(Butler IV, 2000 #275)) and 6.3mm (CL) when cultured under laboratory conditions (Goldstein et al. 2008). Shortly after settlement it acquires a cryptic coloration helping to protect it from predators (Lozano-Álvarez 1994, Stockhausen et al. 2000) (Photo 1-1).

Juvenile stage: *P. argus* juvenile lobsters, stay for 1-2 years in back reef nursery habitats until near maturity (Briones-Fourzán et al. 2000, Butler et al. 2011). The early benthic phase, like all spiny lobsters is typically cryptic sedentary and solitary, rarely leaving shelter, where the habitat is mainly substratum-rocks, coral rubble, algae or seagrass which provides

protection for the young lobsters (Lipcius et al. 1997).

Young benthic stages of *P. argus* will typically inhabit branched clumps of red algae (*e.g. Laurencia sp., Lobophora variegata*) mangrove roots, seagrass banks, or sponges, and feed on local invertebrates found within the lobster's algae microhabitat (Briones-Fourzán & Lozano-Álvarez 2001b, 2013). The young *P. argus* are solitary and exhibit aggressive behaviour to ensure that they remain solitary (Berril 1975). Studies suggest that the habitation of macroalgae by the juvenile lobsters provides protection to the vulnerable individuals from predators while providing easy access to food sources (Marx & Herrnkind 1985, Herrnkind et al. 2001, Saul 2004, Briones-Fourzán & Lozano-Álvarez 2013, Gutzler et al. 2015).

Adult stage: Larger juveniles typically move out from shallow areas to the deeper reefs, where reproduction occurs, and this species is known for its queue-style mass migrations sometimes involving journeys of 2–3 days across the Caribbean, induced by particular weather conditions such as cold fronts and tropical storms (Lipcius & Eggleston 2000).

Adult lobsters of 75-91 mm in carapace length (CL), the average size at female maturity, estimate 2-3 years of age (Fonseca-Larios & Briones-Fourzán 1998), inhabit coral reefs, forage in nearby seagrass beds, and undergo migrations for mating (Herrnkind 1980, Bertelsen 2013, Briones-Fourzán & Lozano-Álvarez 2013).

Lobster movements and reproductive behaviour are factors that may determine for finding differences in sex ratios, and variations in population densities in specific areas or at certain depths in ecologically similar locations within the same fisheries (Eggleston & Parsons 2008, Goñi et al. 2010, Ley-Cooper et al. 2014). Only by integrating alternative behavioural strategies into population models, can we begin to understand their influence on fishery management models; where critical insights into the role of behavioural variation in fishery management can be catchability, and the influence of behaviour on the use and effectiveness of marine reserves (Eggleston et al. 1990, Childress & Steven 2006, Eggleston & Parsons 2008).

Reproduction in *P. argus* occurs more frequently in deeper reef environments (>10 m in BC and SK depending on the area), once mature individuals have made the transition from the shallow seagrass nursery to the coral reef system (Lipcius & Cobb. 1994). Spawning

season is in the spring (March-May) and summer (June-September), although autumnal reproduction also occurs on a lower scale (Kanciruk & Herrnkind 1978, Lipcius & Herrnkind 1987, Fonseca-Larios & Briones-Fourzán 1998). It has been reported in the Florida Keys USA, that the initiation of spawning is related to water temperature with an optimal water temperature for mating of 24°C (Lyons 1980). Spawning generally begins when individuals reach carapace lengths of around 70mm, and reproductive fecundity is dependent upon the size of the individual as well as the geographic area where the lobster lives (Lipcius & Eggleston 2000). Reproductive efficiency for a given size in a given area can be determined according to the relationship between fecundity and carapace length (Kanciruk & Herrnkind 1976).

Reproductive behaviour and fecundity will be further discussed in the chapters and sections regarding the possibility of introducing “casitas” into the BC Biosphere Reserve (Chapter 4). Maximum reproductive capacities are achieved when a size between 100 and 130 mm in carapace length is reached (Lyons et al. 1981). Choice of mate is determined by the female as well as inter-male aggression, where larger males will prevent a smaller male from courting a female (Lipcius & Cobb. 1994). Whilst some females may mate only once during a season, males can fertilize multiple females (Lipcius 1986). Females bearing eggs usually live in solitary dens and infrequently forage for food (Atema & Cobb 1980, Lyons et al. 1981). Large adult females produce more bR.ds, as well as spawn eggs earlier in the reproductive period than younger females as younger individuals moult earlier in the reproductive period. In the Mexican Caribbean, studies have shown that the reproductive season spans from March to November, with significant peaks in August-September (Briones-Fourzán et al. 1997).

Females have outnumbered males in offshore populations in Florida (Herrnkind 1980), although this was not reported in the sex-ratio lobster population off BA SK Mexico, where fully mature females, particularly those bearing eggs, were very scarce when sampled off-shore using traps (Lozano-Álvarez et al. 1993). Numbers of gravid females were possibly underestimated in off-shore shelf samples due to the availability of natural shelter in BA SK (Lozano-Álvarez et al. 1993), as considerable evidence suggests that traps fail to sample gravid females (Herrnkind 1980). In any case, sex ratios and density proportions found in different fisheries may be influenced by sampling or fishing methods, affected by local migrations or reproductive behaviour dynamics of the species, and also influenced by ecological or environmental factors in each location, hence the importance of incorporating

these factors into fishery management models in order to limit bias in results (Eggleston & Parsons 2008, Goñi et al. 2010).

Given the wide distribution of *P. argus*, the capacity of this species to move between different depths and occupy distinct types of habitats throughout the ontogenic life cycle (Acosta & Robertson 2003, Bertelsen 2013, Briones-Fourzán & Lozano-Álvarez 2013), it is a difficult task to determine independent population structures and limits (Truelove et al. 2015), as geographical boundaries for stocks are not necessarily easily defined by the location in which they are found (further reviewed and discussed in Chapter 9.3.1. section 9.3.1.1.1).

1.4.2 Fishery Biology

Some very complex methodological procedures have been developed for carrying out stock assessments and for bio-economic evaluation of lobster fisheries (Seijo & Fuentes 1989, Chávez 2005, Puga et al. 2005, Gardner et al. 2013). In some cases these have led to important management decisions for guiding fishing effort and practices as in the lobster *P. cygnus* fishery in Western Australia (de Lestang et al. 2012). The importance of accounting for economic costs when making environmental-management decisions subject to resource constraints has been increasingly recognized in recent years (Bellchambers et al. 2009, Salomon et al. 2012, Bellchambers et al. 2014).

1.4.2.1.1 Age and Growth Rates

Even though there is vast amount of literature on *P. argus* species, information on growth and aging is relatively scarce (Lozano-Álvarez et al. 1991b, de León et al. 2005, Ehrhardt 2008, Bevacqua et al. 2010). This is partially due to restrictions on manipulating this species in laboratory conditions (Maxwell et al. 2007), and when assessing wild populations using recapture techniques, there is a risk of tag loss (i.e. from moulting), tag reporting, induced mortality, and other factors will influence estimates (Sweat 1968, Dubula et al. 2005). Consequently, length data which is substantially easier and less costly to attain has been the dominant source of information used to estimate growth in *P. argus* (Photo 3-1). Most age approximations are based on size and growth data, where the length-at-age relationship has been described by applying the von Bertalanffy growth model (de León et al. 2005). Important quantitative information that exists on growth for this species at various locations in the MBRS region has previously been compiled by different authors such as González-Cano (1991) and Arce et al. (2001) and at regional FAO workshops (FAO 2001).

When length data is obtained from local catches, equations may vary and it is possible to adjust values to estimate lobster age from CL, enabling age frequency analysis, and production of age structure histograms from trapped lobsters. However the geographical proximity between Cuba and Mexico has advocated using the same biological parameters in stock assessments for the Banco Chinchorro fishery using different methods including age structured depletion analysis (González-Cano et al. 2001, Sosa-Cordero 2003) and Fishery Simulation Models-FISMO (Chávez 2005),(Ley-Cooper & Chávez 2009). Comparison between Florida and Cuba, evidence the differences that exist between the estimated growth parameters in distinct populations (Maxwell et al. 2007). This occurs regardless of the fact that locations may be relatively close to each other, may share a common larval pool source, or are even part of a large Meta-population (Briones-Fourzán et al. 2008, Butler et al. 2008, Ehrhardt et al. 2010b) which in turn poses questions regarding the interdependence that may exist in terms of parental stock, a factor reviewed in more depth in section (1.5).

Because size has been considered as a poor proxy for age of crustaceans because of numerous environmental, density-dependent, and fishery-related factors found in the field, an established technique for aging crustaceans, employing histologically determined lipofuscin content in the nervous system, was developed using known-age of *P. argus* lobsters reared in the laboratory at ambient temperatures, by analysing the presence of lipofuscin in eyestalk neural tissue (Maxwell et al. 2007). In the study by Maxwell et al. (2007) analysing neurolipofuscin that accumulated with age, there was no difference in the concentrations of males and females of the same age; the overall trend was linear with indications of seasonal oscillation, where data suggested a maximum potential lifespan for *P. argus* of about 20 years, whereas growth began to approach an asymptote after 3 years. Although neurolipofuscin may be valuable for estimating age of wild-caught specimens, the results suggest a slightly higher growth rate for *P. argus* than that estimated from most previous studies carried out in the wild using mark and recapture techniques (Lozano-Álvarez et al. 1991b, Sharp et al. 2000).

1.4.2.1.2 Natural Mortality

Natural mortality for Palinurid's primarily occurs in the case of larvae, puerulus, during juvenile stages and moulting (Groeneveld et al. 2013). Early benthic spiny lobster juveniles are most vulnerable to predation and suffer high mortality from an array of fishes and motile invertebrates, e.g., crabs and octopus, despite adaptations that include the use of physical refuges, dispersed distributions, camouflage, cryptic behaviour, and nocturnal activity

(Eggleston et al. 1990, Smith & Herrnkind 1992, Lavalli & Spanier 2010). As they grow, benthic juveniles increasingly attain a “size refuge” from predation and undergo ontogenetic changes in their use of shelters and habitats and in terms of level of sociability (Briones-Fourzán & Lozano-Álvarez 2001b, Butler et al. 2006, Briones-Fourzán & Lozano-Álvarez 2013).

Lobster growth and natural mortality estimates are needed to improve lobster stock assessments and improve general evaluations of the efficacy of local fishing regulations. In their review, Lavalli and Spanier (2010), suggested that natural mortality estimates that have been made for *Palinurus* spp. show a fairly low predation rate of adults with a lifespan of 15 to 30 years, whilst mortality rates of early juveniles, are thought to be extremely high (80 to 96%) (Herrnkind & Butler 1994, Phillips et al. 2003a).

Information on growth and natural mortality of spiny lobsters are some of the most basic population parameters required for effective fishery management (Bertelsen & Matthews 2001b, Bertelsen 2013). Substantial differences in lobster growth between the SK and BC populations may greatly alter the estimates on age at which recruitment to these fisheries is calculated. The effects of growth estimates and natural mortality may differ considerably if lobsters happen to grow faster or slower than it has been estimated up to this date. In BC and SK local estimates for lobster do exist (Lozano-Álvarez et al. 1991b, Ramírez-Estévez et al. 2010), but differ with regard to other locations where *P. argus* is also found and distributed (Ehrhardt 2008). Thus, it is probably necessary to develop a unique age length relationship for each MPA, in order to interpret information on growth, recruitment, maturation, longevity, and mortality with current data.

It is uncertain whether lobster growth and population dynamics in both SK and BC areas are equally alike. There is always the possibility that BC could resemble the island model where juvenile habitat is different to SK, as the latter could more closely resemble the continental model, which characteristically has better juvenile habitat and improved growth rates (Hunt & Lyons 1986). In any case, whether the latter theory applies or not can only be verified with updated local population age evaluations, as these would provide more accurate stock assessments and modelling techniques.

Panulirus argus populations have been affected by very high fishing pressure for such a long period of time, making it difficult to distinguish natural mortality rates from mortality rates caused by fishing (Herrnkind 1980). Hurricanes have a significant impact on juvenile

mortality (Cruz et al. 2001, Beltrán-Torres et al. 2003), with increased regional frequency and intensity in the region possibly related to climate change (Caputi et al. 2013, Puga et al. 2013). Estimates by the assisting scientists at a regional FAO workshop for assessment of natural mortality for this species were agreed to range between 0.3-0.4 year⁻¹ (Arce et al. 2001), and efforts to define these parameters continue in many fisheries (de León et al. 2005, Ehrhardt 2008, Sosa-Cordero 2014).

1.4.2.1.3 Fishing Mortality

Seijo and Caddy (2000) describe fishery indicators as variables that measure the state of the fishery, which can assume discrete values believed to represent critical situations, and refer to variables derived from monitoring a fishery; they can assume discrete values conveying information believed to be relevant to proper management for exploiting the resource. In order for the indicators to be meaningful they should explicitly account for the space, time and certainty aspects of fishery systems.

In any area such as SK and BC where limits and boundaries may be geographically or conceptually defined (see section 1.6.3, as well as review and discussion 9.3.1.1.1), lobsters can either be captured by the fishery, emigrate, or die of natural causes, and tagging studies may help to develop an estimate of fishing mortality (Lozano-Álvarez et al. 1991b, Frusher & Hoenig 2003, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). Tagging can help by providing a rate of emigration and immigration to and from the study sites, by identifying whether lobsters moved from these study sites elsewhere to areas where they remain unfished, while indicating lobsters that die during the study as the result of natural mortality (Hearn et al. 1987, Lozano-Álvarez 1992, Hoenig et al. 1998, Ley-Cooper et al. 2013).

Studies conducted during the closed fishing season, help distinguish between fishing and natural mortality in the study areas by identifying removals by the fishery, producing independent estimates of emigration, and dependent on the differences between these estimates it is possible to develop separate seasonal estimates or one overall estimate indicating natural mortality (Lozano-Álvarez 1992, Bertelsen 2013, Ley-Cooper et al. 2014). Fishery indicators should consider heterogeneity in resource distribution in space and time, if they are to provide adequate signs of fishery status taking into account the time dimension when dealing with these dynamic systems (Harford et al. 2015). Use of an indicator to assess whether a target reference point is being achieved must be based on calculations stemming from models that incorporate the population dynamics, the resource users, and resource

managers, where a third dimension of indicators concerns the certainty equivalence of the fishery system being monitored (Seijo & Caddy 2000, Ley-Cooper et al. 2014, Harford et al. 2015).

1.4.3 Recruitment to the population

This thesis focusses on the BC and SK *P. argus* populations, yet it is important to present a general overview of how life cycle stages may affect local and regional population connectivity as part of the more extensive intermixed MBRS Metapopulation (Briones-Fourzán et al. 2008, Butler et al. 2011, Truelove et al. 2014, Truelove et al. 2015). The genetic pool exchange between sink and source populations “panmixia” (Naro-Maciel et al. 2011) may occur as a result of processes related to reproductive activity/egg production, larvae transport and dispersal, pueruli settlement and recruitment, as well juvenile and adult movements and migrations; and the capacity for dispersal at each of these life stages, greatly influences the extent of connections between populations (Palumbi et al. 2009). Part of the difficulty for defining the boundaries of *P. argus* lobster stocks and describing its local population dynamics, resides in the number of biological and oceanographic variables, which may affect the different stages in the life cycle at local and regional levels (Ehrhardt et al. 2010a). These in turn result in many unknown processes taking effect within these populations. Consequently, the interdependence of the BC and SK populations during the different Stages of their life cycles, and the levels of connectivity that occur between and within these populations are still uncertain or unknown in many cases (further reviewed and thoroughly discussed in section 1.5 and 9.3.1.1.1).

1.4.3.1.1 The Phyllosoma larvae phase of *P. argus*:

Most *P. argus* spiny lobsters have one or two reproductive peaks, which occur depending on their geographical location, for example in Mexico this is during late spring and early summer, although egg bearing females are found all year round (Fonseca-Larios & Briones-Fourzán 1998). Spawning occurs in deeper waters near the fringes of the outer reefs and females at egg hatching are abundant in areas with strong water movement (Briones-Fourzán et al. 1997). During the night or early morning, eggs hatch to produce Phyllosomata larvae which initially rise to the surface. As they are carried offshore, phyllosoma migrate between the surface at night and deeper waters during the day (Jeffs et al. 2005, Butler et al. 2011). Post larvae transit from their planktonic pelagic realm to the reef or lagoon benthic nursery using tidal fronts, internal wave slicks, turbulence, and Ekman transport among other

physical forces, each operating in tandem with puerulus behaviour (e.g., selective tidal stream transport, attraction to surface, depth regulation) finally depositing pueruli near coastal areas, where settlement subsequently occurs (Briones-Fourzán et al. 2008, Butler et al. 2011, Muhling et al. 2013).

Capacity for dispersal mainly influences how connected marine populations are, and the main vector for connectivity is thought to be larvae, as their capacity for being transported long distances is generally greater than during other life cycle stages (Palumbi 2003). It has long been assumed that the pelagic larval duration (PLD) of a species is directly related to its connectivity, with longer PLDs resulting in more highly connected populations (Barber et al. 2002). Among *P. argus* there are a multiple currents and other oceanographic factors that influence the movement of water throughout the range of its distribution (Ezer et al. 2005, Briones-Fourzán et al. 2008),(Butler et al. 2008, Muhling et al. 2013) (Figure 1-10 and Figure 1-11). The long period that lobsters spend at the larval stage, traveling on the currents, partially impairs scientist's ability to determine stock boundaries and population limits. Different methods for DNA analysis may be useful in determining some sort of stock structure for *P. argus*; however the extensive larval phase may also limit this tool, as it takes only a few successful migrants to homogenize the gene pool (Saul 2004, Naro-Maciel et al. 2011, Truelove et al. 2014). Studies have also indicated that the presence of local gyres or loop currents in certain locations may influence the retention of locally spawned larvae, and lead to the settlement of larvae in a particular location (Briones-Fourzán & Gutiérrez-Carbonell 1992, Briones-Fourzán et al. 2008, Butler et al. 2008, Truelove et al. 2014).

As extensively discussed in the study by Naro-Maciel et al. (2011), larvae dispersal dynamics, mainly driven by currents during the most prolonged stage in the life cycle, has widely been thought to result in panmixia within *P. argus*. The main tendency in recent studies regarding phyllosoma studies has appeared to corroborate the idea of commonly shared larval sources, which in turn have led to common panmictic pools resulting in genetic intermixing and shared Meta-populations of adult *P. argus* (Truelove 2014, Truelove et al. 2015). The possibility of a regional or even local population structure occurring within a species that has such a prolonged larval phase is unlikely, as the complex relationship between planktonic larval duration and population structure has implications for management with respect to loss of genetic diversity (Naro-Maciel et al. 2011). Identification of distinct source and sink populations, as well defining structure within populations may help in

planning for marine protected areas as well as regional and international coordination (see section 1.5) (Diniz et al. 2005 , Truelove et al. 2015).

1.4.3.1.2 Postlarval Recruitment, and Sources of larval Recruitment

Spiny lobsters infiltrate the coastal zone as short-lived (2–4 weeks) but fast swimming pueruli after remaining a pelagic larval duration for several months (Butler et al. 2011). Metamorphosis of *P. argus* larvae to the puerulus phase occurs offshore near the shelf break from where the non-feeding puerulus is advected or swims onshore. Physical force caused by wind driven or tidally driven currents no doubt plays a role in their cross-shelf transportation (Phillips et al. 2003a, Briones-Fourzán et al. 2008); but the relationship between the magnitude of these forces and puerulus abundance is typically weak (Butler & Herrnkind 2000, Phillips 2006).

Identifying population connectivity and sources of recruitment are fundamental requirements for sound management of exploited marine species (Briones-Fourzán & Gutiérrez-Carbonell 1992, Hunt et al. 2009, Phillips et al. 2010, de Lestang et al. 2012). However, the wide distribution of *P. argus* where a complex array of currents, gyres, and eddies may influence species larval dispersal suggests that there may be some regions that represent significant sources of recruitment, whereas others may essentially recruitment ‘sinks’ (Lipcius et al. 1997). This factor prohibits confined locations/countries from undertaking stock assessments which could be used to develop prediction models that would forecast yield (Phillips et al. 2000, Cruz et al. 2001, Penn et al. 2015).

The importance of measuring levels of postlarval recruitment and abundance for fishery management purposes has been demonstrated. For example studies by: Lipcius, et al (1997), Gutierrez-Carbonell et al. (1992), and Puga et al. (2013). Efforts have been made to quantify *P. argus* throughout the Caribbean, in Mexico (Briones-Fourzán & Gutiérrez-Carbonell 1992), Cuba (Cruz et al. 2001, de León et al. 2005), and Florida (Herrnkind & Butler 1994) yet the high degree of connectivity of this species revealed by genetic, oceanographic and biophysical modelling studies indicates that larval sources may be distant from eventual post-larval recruitment sites, confirming the need for regional management of this shared resource (Briones-Fourzán et al. 2008,, Butler et al. 2008, Naro-Maciél et al. 2011, Truelove 2014).

Microsatellite DNA analysis to identify sources of recruitment has been the latest approach for studying recruitment and connectivity among spiny lobsters (Kennington et al.

2013, Truelove 2014, Truelove et al. 2015). A regional example in the study carried out for Florida's *P. argus* stock by Hunt et al. (2009), indicated that spiny lobsters are highly interconnected in terms of gene flow, at locations along the United States coast and throughout the Caribbean; However, differences in allele frequencies, trends in fixation indices, and the spatial separation of genotypes among several sample locations provide evidence for some level of self-recruitment, as genetic differences were not generally related to geographic distance, and divergent sample pairs were also found in nearby sites. Truelove et al. (2014) also used a microsatellite multiplex protocol for a study of genetic connectivity among *P. argus* between advective and retentive oceanographic regions in the Caribbean Sea. The study together with a biophysical model predicted which oceanographic regions had the highest and lowest levels of larval self-recruitment within the Caribbean seascape, and explored associations between genetic population structure and dispersal barriers in these locations. Their results suggested that sites in Panama and Andros Island in the Bahamas, both located in oceanographic regions with large offshore gyres, were consistently distinct from the rest of the sites in their study. Sites located near the mean surface flow of the Caribbean current were consistently genetically similar to each other, and no evidence of genetic isolation according to distance was found. These findings suggest that oceanographic or environmental drivers rather than geographic distance are more likely influence spatial patterns of gene flow among *P. argus* lobsters.

A comprehensive analysis should ideally consider both dispersal dynamics and genetic differentiation. Only analysing either post larval recruitment and settlement levels, or likewise only evaluating genetic data may neglect ecologically relevant differentiation. Integration of information on ecological and possibly even evolutionary timescales (Ehrhardt & Fitchett 2010) would evidently benefit any analysis. The relationship between sink and source regions needs to be better understood for management purposes, as if any source regions are being overfished, then it appears likely that recruitment to other areas throughout the Caribbean may be impacted (Hunt et al. 2009), which may be occurring in SK and BC.

Recent stock information has failed to conclusively indicate that the population(s) being fished in SK and BC should be considered as separate from those in other areas along the south or northern coast of the State of Quintana Roo or the Caribbean in general. Several years of puerulus settlement data and physical oceanography representing a combined modelling effort on the part of (Briones-Fourzán & Gutiérrez-Carbonell 1992, Briones-Fourzán et al. 2008) suggested the possibility that recruitment of the Mexican lobster stock to

Quintana Roo.-México (including BC and SK), may be partially dependent on ‘upstream’ larvae carried from areas such as Belize, Honduras Nicaragua, and Venezuela to the south of these sites. this possible pattern has also been mentioned by other authors (Sosa-Cordero 2003, Seijo 2007, Briones-Fourzán et al. 2008, Butler et al. 2008, Hunt et al. 2009, Muhling et al. 2013) (See Figure 1-11).

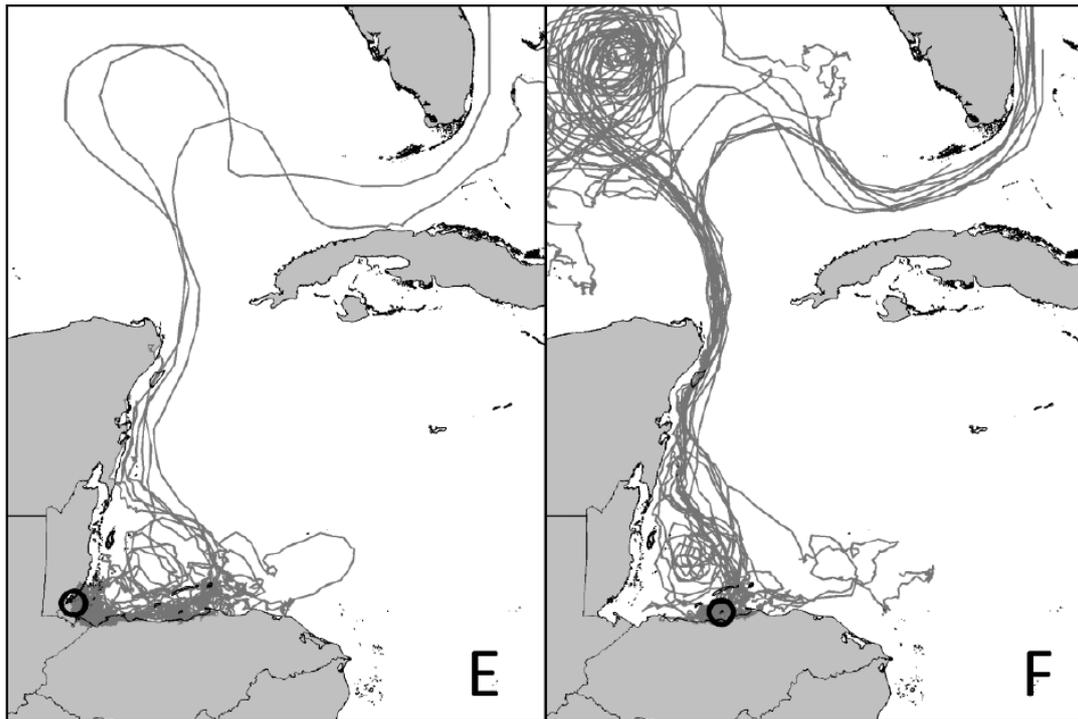


Figure 1-11: From Butler et al. (2011), Truelove (2014) Biophysical Modelling of *Panulirus argus* Larval Dispersal. Examples of the effect of local oceanography on spiny lobster larval dispersal from two larval release sites found south in the Mesoamerican region of the Caribbean Sea. Shown are model predictions of the dispersal of larvae (grey lines) exhibiting ontogenetic vertical migration and released from: (E) “Tres Puntas, Guatemala”, and (F) “Cayos Cochinos, Honduras”.

As the main stream Yucatan current will prevailingly transport larvae in a northbound direction, local spawning is expected to contribute to recruitment in other areas ‘downstream’ from BC and SK (Figure 1-10 and Figure 1-11). However Eckman gyres associated with atolls such as Glovers Reef and Turnefe in Belize and Banco Chinchorro in Mexico, often include southerly bound currents on the western side of coastal banks, showing that larval transport/recruitment is not unidirectional and may also occur in the opposite direction thus

promoting self-recruitment (Muhling et al. 2013). It is therefore possible that oceanographic retention mechanisms return a portion of the larvae to the place of origin (source populations), so that genetic connectivity analysis at a regional level (Truelove et al. 2014) and between SK and BC (Truelove et al. 2015) becomes relevant.

Impacts related to the complex life history and open natures of local populations subject to fishing are relevant to management. The SK and BC fisheries are currently certified by Marine Stewardship Council (MSC) which implies that: “the status of the stock is such that it indicates with a high degree of certainty that it exceeds the point at which recruitment is impaired” (Marine Stewardship Council 2010, MRAG-Americas 2013). Uncertainty exists throughout the Caribbean concerning which are source and sink *P. argus* populations, thus in order to maintain current recruitment levels, Mexican stocks like SK and BC may require management at an international level. It also means that stock assessment models based on stock recruitment relationships (Ley-Cooper & Chávez 2009) are difficult to validate and accomplish.

1.4.3.1.3 Algal-phase Juveniles, Juveniles and Sub-adults:

Once the planktonic Stages *P. argus* lobsters have concluded, the pueruli settle down in shallow benthic environments to grow into algal phase juveniles. Laboratory studies on behavioural enhancement of onshore transport carried out by Goldstein and Butler (2009), have indicated that *P. argus* pueruli use chemical and pressure cues during onshore transportation and for selection of settlement habitat, emphasizing the important role of behavioural responses to physical cues in the recruitment of this species during the pueruli stage: (1) they are repulsed by great variation in salinity (i.e. 25 or 50 ppm), compared to the seawater average of 35 ppm; (2) they are attracted to coastal seawater, particularly seawater containing chemical cues derived from red macroalgae, where they tend to settle; and (3) they settle when pressure cues are similar to those found in shallow (<7 m) lagoon habitats, where most natural settlement occurs; likewise macroalgal odours accelerate the development of pueruli to reach the benthic juvenile stage (Goldstein & Butler 2009), a transition that may significantly reduce their risk from predators (Acosta 1999).

P. argus postlarvae supply is variable and uncertain in many areas, yet sufficient nursery habitat is crucial for successful postlarval settlement, as well as the growth and survival of juveniles that are recruited to fisheries. Notably, large shallow coastal zones with habitat suitable for nurturing juvenile lobsters (Herrnkind & Butler 1994, Cruz et al. 2001, Briones-Fourzán &

Lozano-Álvarez 2013) are the areas where the greatest *P. argus* fishery production takes place in the Caribbean. Local recruitment is not necessarily highest in areas to which the highest concentrations of postlarvae are destined (Herrnkind & Butler 1994, Lipcius et al. 1997, Briones-Fourzán et al. 2007). The potential for habitat limitation to impact *P. argus* recruitment has been experimentally demonstrated in the Bahamas (Lipcius et al. 1997), and Mexico (Eggleston et al. 1990, Sosa-Cordero et al. 1998, Briones-Fourzán & Lozano-Álvarez 2001b, Briones-Fourzán et al. 2007). Macroalgal rich hard-bottom and secondarily seagrass are the preferred settlement habitats for the species, but areas with ample crevice shelters are crucial for high survival of later stage benthic juveniles (Marx & Herrnkind 1985, Eggleston et al. 1990, Acosta & Butler 1997, Bertelsen 2013, Briones-Fourzán & Lozano-Álvarez 2013).

P. argus growth in juveniles is rapid with most reaching a carapace length (CL) of 60-70 mm within about two years after settlement (Herrnkind 1980). Once the lobsters reach about 70 mm CL they begin to sexually mature, and emigrate from the nursery to deeper offshore reef environments. Juveniles are mainly distributed in shallow areas (<10 m), such as bays and reef lagoons covered in submerged vegetation, whilst adults occupy a greater diversity of habitats including those in deeper reefs and rocky areas (Briones-Fourzán & Lozano-Álvarez 2013). In Quintana Roo adults have been documented in depths of 60 m or more (Lozano-Álvarez et al. 1991b, González-Cano et al. 2000a). Areas in Quintana Roo and the Yucatan such as Bahía de la Ascension (BA) and Bahía del Espíritu Santo (BES) in SK Biosphere Reserve (Figure 1-6), and the eastern coast of the Yucatan Peninsula are nursery areas for juveniles of *P. argus*, as they are shallow with a sandy sea bottom and seagrass (*Thalassia tetudinu*, *Syringodium filiforme*, *Halodule wrightii*) and macroalgae (*Laurencia spp.*, *Halimeda spp.*, *Udotea spp.*, *Penicillus spp.*, *Euchema isisforme*, *Acetabularia spp.*) and have, with transparent relatively calm waters (Briones-Fourzán et al. 1997, Briones-Fourzán & Lozano-Álvarez 2013).

In extensive sea grass areas' where natural refuge is scarce and heterogeneously dispersed, as is the case in the Bahía de Ascension and Espíritu Santo Bays in SK, artificial refuges known as casitas (see section 1.6.4.1.1) are able to serve as refuge to groups of lobsters (Briones-Fourzán & Lozano-Álvarez 2001a). *P. argus* are an ontogenetic species which will change habitat as they grow and advance in the life history, larger animals will eventually abandon the natural and artificial refuges "casitas", yet these will continue to attract and recruit other juveniles and sub adults (Arce et al. 1997, Sosa-Cordero et al. 1998, Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán & Lozano-Álvarez 2013).

Studies of juvenile *P. argus* in Florida have estimated 96-99% mortality rates during the first year after having settled (Herrnkind & Butler 1994). Group coordinated defence within a refuge, is a type of social behaviour for *P. argus* and has been documented as efficient for counter attacking predators (Herrnkind et al. 2001, Briones-Fourzán et al. 2006), considerably diminishing mortality (Eggleston & Lipcius 1992, Briones-Fourzán et al. 2007, Briones-Fourzán & Lozano-Álvarez 2013). This mechanism for defence and survival is enhanced by casitas in habitats where refuge is scarce (see Chapter 4) (Briones-Fourzán & Lozano-Álvarez 2013). The latter is contrary to what was published by Gutzler et al. (2015) who argues that casitas in nursery areas (where shelters are abundant), may serve more as an attractor than an enhancer device, which increases juvenile mortality and vulnerability to predators, serving as “death traps”, yet details will be further discussed in section 1.6.4.1.1. Due to the presence of *P. argus* virus 1 (Pav1) (Behringer et al. 2011) disease may be an additional potential bottleneck for reaching adulthood, further studies as the one recently been documented in the BA bay in SK (Candia-Zulbarán et al. 2012) and BC (Ramírez-Estévez et al. 2010) are still necessary.

Puga et al. (2008) carried out ecological studies on spiny lobster habitats in Cuba, and recognize several fundamental environmental conditions as negatively impacting habitats, where juvenile recruitment occurs including: 1) decreased amounts of naturally and anthropogenic ally produced nutrients owing to dam construction that interrupts natural runoff of nutrient rich fresh water into the spiny lobster habitat 2) increased salinity in juvenile habitats affecting larvae and prey species, 3) incidence of major and more frequent hurricanes impacting habitat structure, and 4) significant coastal zone development, including highways that impacted inshore-offshore water exchange. Experimental studies in Florida confirm the negative effects of siltation, extreme salinity, and the loss of physical structure in puerulus and juvenile lobster survival (Marx & Herrnkind 1985), (Butler & Herrnkind 1997). Many Regions can be viewed as ecological mosaics, where processes that drive local recruitment vary locally depending on spatial and temporal patterns of habitat structure and puerulus supply (Butler et al. 2006). Effects from environmental conditions on recruitment may be independent of fishery exploitation, impacting the adult stock two to three years after they occur.

As previously mentioned when *P. argus* reach a carapace length of approximately 20mm (CL) individuals begin the “onset of sociality”, seek out conspecifics, and the change in behaviour coincides with an ontogenetic habitat switch from vegetation to diurnal dwelling in different refuges such as sponges, corals or rock crevices (Butler et al. 2006). This is when

adult stages begin, as well as gradual loss of the post settlement pattern, and strong social facilitation behaviour including queuing starts (Childress & Herrnkind 1997).

1.4.3.1.4 Large Juveniles, Subadults and Adult Lobsters:

This section only presents general aspects, as further details and specific aspects of recruitment are reviewed and discussed in each chapter of this thesis. Comprehensive reviews on this theme and related aspects have been carried out by several authors including juvenile and adult ecology (Butler et al. 2006), behaviour (Childress & Steven 2006), and more recently in the book edited by Phillips (2013) in chapters related to *Panulirus* species, regarding essential habitats Briones-Fourzán and Lozano-Álvarez (2013), ecology, movements and other aspects (Phillips et al. 2013).

When adult stages begin with strong social facilitation, shifts in habitat use, and behaviour including queuing starts (Childress & Herrnkind 1997), co-habitation of dens is more common and distribution is mainly determined by the location of larger crevices. Large juveniles and non-reproductive adults of most Palinurids can be identified by their occupation of dens, where the number of solitary and co-occupant lobsters may vary according to locality and season. Local occupants at any time include a mixture of long term residents from 1 to 3 dens (used interchangeably) in the vicinity and transients, either immigrants or past residents that have been elsewhere and returned. Many occupants can re-orient themselves and return back to a den, even after being displaced several hundred meters or up to a kilometre away, suggesting the selective and repeated use of known shelters by older adults (Olsen et al. 1975),(Butler et al. 2006).

Throughout most of their adult life *P. argus* distribution and behaviour is somehow linked to shelters and refuges where they dwell during the day, leaving to forage at night. Evening movements that occur within the home range are directed, as lobsters are apparently aware of their location at all times and can find their way back to the den of origin, even if detours are caused by predators or divers; this pattern is called “homing”. Patterns of movement among *P. argus* fall into the following categories: homing, nomadism and migration(Herrnkind 1980). Nomadism is the movement that juvenile lobsters make away from the nursery habitat and to offshore reefs, whilst migration is the direct movement of an entire population or sub-population over a long distance for a given period of time (Herrnkind 1980),(Saul 2004),(Butler et al. 2006, Phillips 2013, Phillips et al. 2013). All movement categories are somehow related to the occurrence of recruitment processes, as they have

considerable effects on the timing, direction and abundance patterns that define distinct local population dynamics (see chapters 5, 6 and 7).

1.4.3.1.5 Movements and migration

Population dynamics and fishery aspects of *P. argus*, movements and migration patterns have been studied extensively in relation to recruitment in order to determine immigration, emigration, sustainability and the mixing of stocks (Kanciruk & Herrnkind 1978, Herrnkind 1985, Childress & Steven 2006, Bertelsen 2013, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Harford et al. 2015). Mass movements of individuals occur annually throughout the geographic range of the species, yet specificity of the phenomena is dependent on latitude and climactic factors. Thus reported seasonality for this phenomena is defined as October for Bermuda, late October and early November for the Bahamas Florida and Cuba, and December for the Yucatan and Belize (Kanciruk & Herrnkind 1978, García et al. 1991, González-Cano 1991, González-Yañez Akim et al. 2006, Bertelsen 2013, Ley-Cooper et al. 2014).

Biological information about the species indicates that mass migratory behavioural changes observed in *P. argus* are related to individuals migrating in order to evade stress caused by cold and turbid water in the winter. In Florida for example the first autumn storm usually brings a severe drop in water temperature of about five degrees centigrade, as well as high northerly winds of up to 40km/h which cause large sea swells (Herrnkind 1985). The shallow regions that the lobsters exploit during the summer months become turbid and cold, impelling the diurnal migration of thousands of lobsters as they attempt to evade these conditions. *P. argus* is highly susceptible to severe winter cooling and will exhibit reduced feeding and locomotion at temperatures 12-14⁰C; moulting individuals usually perish under these conditions (Kanciruk & Herrnkind 1978). *P. argus* has been reported to initiate the migratory behaviour of queuing into a single file formation by visual or tactile stimuli of other migrating individuals. Queuing is maintained by establishing contact between the antennules of one individual and anterior walking legs of another. Biologically, queuing behaviour is an important hydrodynamic drag reduction technique for the migration of individuals over long distances (Kanciruk & Herrnkind 1976, Herrnkind 1985).

Mark and recapture of individuals in order to study movements and migrations among lobsters enables tracing individuals for prolonged periods of time and distances, and has also been used to estimate the relationship between movement and recruitment patterns (Frusher

& Hoenig 2003, Dubula et al. 2005, Ehrhardt 2008, Ley-Cooper et al. 2013). Studies have found that during migration, individuals tend to move large distances of up to 30-50km (Herrnkind 1980, Herrnkind). Migratory movement lasts for variable periods of time and is believed to be dependent on the total number of migratory lobsters. The migration is also thought to occur to curtail the overcrowding of shelters at their final destination. It is believed that once individuals reach sheltered habitats located in deeper water, the migratory queuing behaviour ends and the lobsters disperse (Herrnkind et al. 1973, Kanciruk & Herrnkind 1978). Tagging studies in the bays of SK have shown that both short and long distance movements occur in BA (Lozano-Álvarez et al. 1991b), and have been reported from the northern bay BA to the southern BES, as well as from the shallows (<20 m) to the deep unfished areas (>20m) and vice versa (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). This highlights the importance of understanding these patterns in relation to population dynamics, recruitment and exploitation patterns (for details see chapters 5, 6 and 7).

1.5 Genetic Population structures of *Panulirus argus*

Using genetic markers to identify population structure is in vogue, and technology is rapidly changing as the power of mtDNA to identify population structure in marine organisms is relatively limited compared to allozymes, microsatellites, and single nucleotide polymorphisms (SNPs) which are now the most commonly used types of population genetic markers (Truelove 2014). Genetic methods are widely used for identifying genetically distinct stocks within larger populations, monitoring genetic diversity, and mapping connectivity among marine populations (Hauser & Seeb 2008, Waples et al. 2008, Hunt et al. 2009, Truelove 2014). Microsatellites are polymorphic, non-coding, regions of the genome, where a small sequence of DNA (only a few bases long) is repeated a varied number of times. The variability in the number of repeating units is created when the repeats are commonly added or removed during DNA replication and recombination. For this reason, microsatellites are particularly useful to fisheries for population genetic studies due to their high levels of intra-specific variability in many taxa allowing for high statistical power for population assignments, parentage analyses, and kinship reconstruction (Diniz et al. 2004).

Over the last decade microsatellites have allowed for large quantities of data to be collected indicating the population structure of marine species (Hemmer-Hansen et al. 2007), and studies have demonstrated that the coexistence of multiple genetically distinct populations within a species is a common phenomenon (Waples et al. 2008)). Hunt et al.

(2009) carried out a genetic survey of population connectivity in *P. argus*, where microsatellite DNA loci were used to genotype specimens from 17 locations throughout U.S. and Caribbean waters. In the adult survey, significant differences in allele frequencies of samples were observed among 42 of the 136 tested pairs. There was evidence of spatial structure among populations, and outlying sample locations included St. Kitts, Venezuela, Bimini, North Carolina, and the Dominican Republic. Overall this study led to the abandonment of the idea that Florida was sourced by self-recruitment, as results indicated that spiny lobsters are highly interconnected in terms of gene flow in locations along the coastal United States and throughout the Caribbean, even if differences in allele frequencies, trends in fixation indices, and the spatial separation of genotypes among several sample locations, provided evidence for some level of localized self-recruitment at those locations.

For management purposes, genetic analysis using microsatellites is useful for assessing and identifying differences in population structures within and between geographically separated areas such as SK and BC, which are currently thought to be interconnected by default, mainly because of their relative proximity. These techniques may also help to reveal levels of connectivity between discrete size classes within defined areas of distribution at different levels in neighbouring MPA's such as BC and SK, or at regional levels-MBRS (Truelove 2014, Truelove et al. 2014, Truelove et al. 2015).

1.5.1 Genetic Context in the Mesoamerican Barrier Reef Region

Identification of distinct source and sink populations, as well as defining structure within populations may help define common strategies for marine protected area planning, and regional or international coordination (Diniz et al. 2005). Besides some genetic studies (Naro-Maciel et al. 2011), previous authors have corroborated the idea of commonly shared larval sources in the Caribbean and especially within the MBRS in Central America (Briones-Fourzán et al. 2008, Butler et al. 2008, Butler et al. 2011, Truelove et al. 2014). However as a collaborative project linked to this thesis, recent efforts for studying connectivity between MPA's in the MBRS (Truelove et al. 2014), and specifically in the BC and SK lobster populations (Truelove et al. 2015) have been carried out.

The genetic studies using microsatellites by Truelove et al. (2014) have confirmed high levels of connectivity from common panmictic pools of genetic intermixing and shared meta-populations of adult *P. argus* lobsters at a regional level within the MBRS (see Figure 1-12), yet findings also suggested that *P. argus* populations may not be as genetically

homogenous as mtDNA studies had previously concluded (Truelove 2014). The main objective of the research was to use direct (e.g. kinship analysis) and indirect (e.g. F_{ST} -based analyses of genetic differentiation) techniques to uncover spatial patterns of connectivity between MPAs in the Central American region of the Caribbean Sea including the BC and SK MPA's. The spatial scale of this study spanned the entire range of the MBRS and also included more distant locations outside the boundaries of the MBRS such as La Moskitia region of Honduras, the Bocas del Toro MPA in Panama, and finally the Alacranes Reef MPA in the Gulf of Mexico (see Figure 1-12).

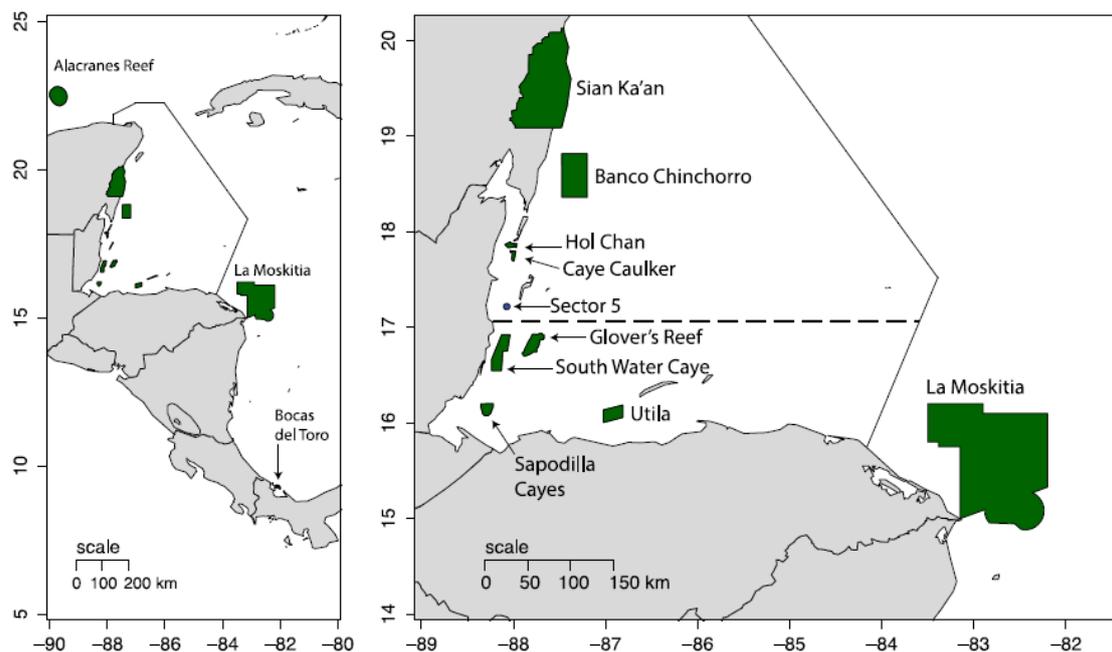


Figure 1-12 From (Truelove et al. 2014) Map of Marine Protected Areas in Central America from which spiny lobsters were collected. The left panel shows the entire spatial scale of the study with the black polygon representing the boundaries of the MBRS. The right panel provides a finer scale map of the marine protected areas in the MBRS from which spiny lobsters were collected. MPAs north of dotted line are referred to as northern MBRS MPAs, and those south of the dotted line are referred to as southern MBRS MPAs. All MPAs are highlighted in green. (Note Sector 5 is a Belize Fisheries Department spiny lobster monitoring site and the boundaries of the La Moskitia conservation zone are not yet officially declared).

The information concerning levels of lobster population connectivity Truelove et al. (2014) found that these are high among spiny lobster populations residing in MPAs in Central America. The Principle coordinates analysis (PCoA) of pairwise comparisons of F_{ST} indicated

that Alacranes Reef, Hol Chan, Caye Caulker, and Sapodilla Cayes were all outliers, suggesting that they may be more differentiated from the other MPA's. Sian Ka'an, Banco Chinchorro, Sector 5, South Water Caye, Glover's Reef, Utila, and Bocas del Toro all clustered together suggesting these were not differentiated from one another. On the other hand the spatial principle components analysis and interpolation of mean pairwise F_{ST} at each MPA both suggested that MPAs in the northern MBRS were genetically differentiated from MPAs in the southern MBRS and from Bocas del Toro in Panama. The interpolation of the spatial principle component eigenvalue with the greatest amount of global structure suggested that spiny lobsters from Caye Caulker, Hol Chan, **Sian Ka'an**, and Alacranes Reef were more differentiated from spiny lobsters from all other MPAs in terms of positive spatial autocorrelation and genetic variance. The interpolation of F_{ST} suggested that spiny lobsters from Hol Chan, Caye Caulker, and Alacranes Reef were more differentiated from spiny lobsters from all other MPAs in terms of mean pairwise F_{ST} values. No evidence of isolation by distance was observed among MPAs ($P = 0.39$).

Given the extensive dispersal capacity of *P. argus* larvae (Briones-Fourzán et al. 2008, Butler, 2011 #286, Naro-Maciel et al. 2011), it is not surprising that the study by Truelove et al. (2014) confirmed that levels of genetic connectivity were high between *P. argus* populations residing in MPAs in Central America-MBRS. Despite this outcome, the study also found low but significant levels of genetic differentiation among both northern and southern MPAs in the MBRS, which were not necessarily attributed to geographic isolation (Hogan et al. 2011). The MPA's in the northern MBRS contained significantly more individuals that were genetically determined outliers or "migrants" than southern MPA's ($P = 0.008$, $R_2 = 0.61$), which may have contributed to the higher levels of genetic differentiation which were observed in the results. The increased "immigration" (statistical nomination) to local populations in the northern MBRS also potentially explains the high genetic differentiation observed among northerly MPAs, and the dissimilarities with respect to the southern MPA's found in Belize and Honduras (Truelove et al. 2014).

The results obtained by (Truelove et al. 2014) contrasted to previous mtDNA studies of *P. argus* (Silberman et al. 1994, Naro-Maciel, 2011 #256), as findings suggest that *P. argus* populations may not be as genetically homogenous as other authors had previously concluded. The high level of connectivity among MPA's provides additional evidence of the importance of international cooperation in the management of *P. argus* lobster fisheries.

However, uncertainty regarding the ecological and physical drivers of genetic differentiation in Northern MPAs implies that managers should hedge against uncertainty.

1.5.2 Population genetics in Sian Ka'an and Banco Chichorro

Kennington et al. (2013) showed that natural populations of most species can be subdivided into separate subpopulations or demes in which random mating takes place. When there is subdivision, or population structure, genetic variation (the presence of two or more forms of a gene or alleles) within the species exists at two levels: 1) genetic variation within local populations and 2) genetic variation between local populations. The existence of population structure within a species suggests there are strong barriers to demographic exchange between populations. This is because even small amounts of gene flow between populations are enough to prevent large allele frequency differences from establishing.

Relevant to this thesis, and an aim of the local genetic study by Truelove et al. (2015) was to investigate population genetic structure of *P. argus* at two levels: (1) spatially between the MPA's of SK and BC; and (2) temporally within these MPA's; by genotyping individual lobsters using bi-parental inherited microsatellite loci. To explore temporal changes in the levels of population structure, cohorts were defined semi-arbitrarily by estimating the age of individuals based on knowledge from previous research of *P. argus* growth rates in SK and other areas in the Caribbean (Phillips et al. 1992, de León et al. 2005, Ehrhardt 2008{Lozano-Álvarez, 1991 #93). Analysis of population structure between cohorts was carried out considering it may have provided an additional level of resolution that could be used to improve our understanding of the local complex spatiotemporal population dynamics of the *P. argus*. Details of the methods used for the analysis of this section of the study may be found in (Truelove et al. 2015).

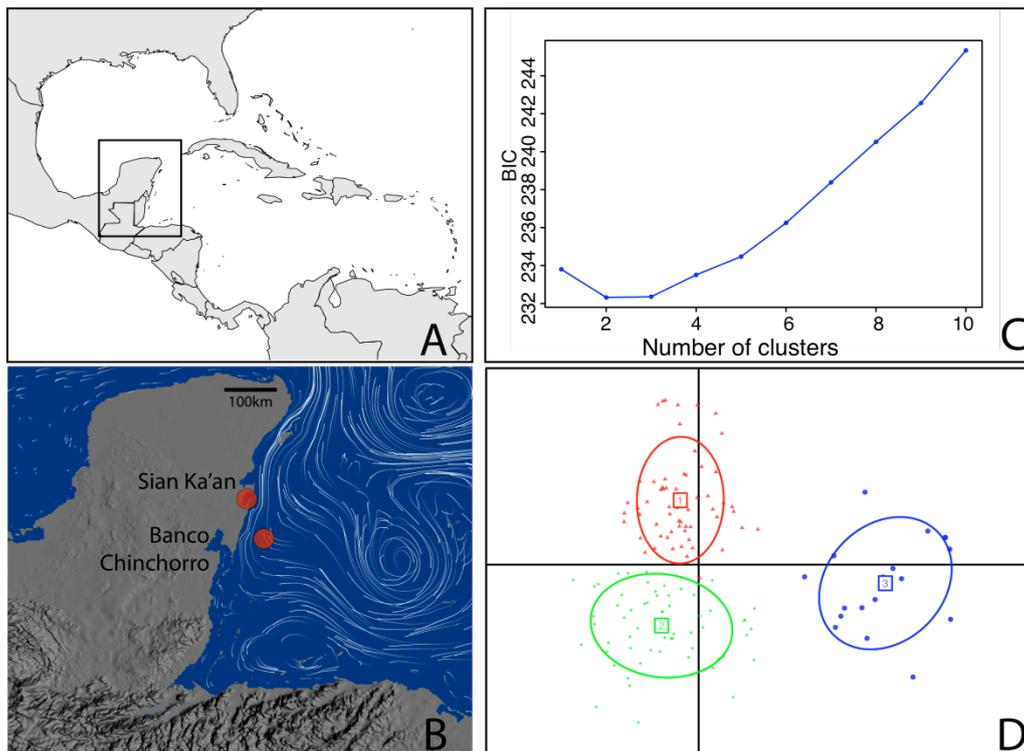


Figure 1-13: From (Truelove et al. 2015). Map of study Sites and *K*-means clustering analysis. A) Regional map of the study area with the sampling sites located within the inset in panel B. B) approximate locations of sampling sites in Sian Ka'an and Banco Chinchorro marine reserves in Mexico. The NASA/GSFC Scientific Visualization Studio provided flow data from the ECCO2 model to produce an image of Caribbean ocean currents. C) Plot of Bayesian Information Criterion (BIC) values used for selecting the number of clusters for the discriminant analysis of principle components (DAPC) method. The lowest BIC values indicate the optimal numbers of clusters. D) Subdivision of clusters employing the DAPC method. Unique genetic clusters are indicated with different colours (red = cluster 1, green = cluster 2, and blue = cluster 3).

From the Biosphere Reserves of BC and SK, a total of 140 individuals were genotyped for 14 microsatellite loci in the study by Truelove et al. (2015). A summary of the results found were that across all loci and populations H_0 was consistently lower than H_S suggesting the potential for null alleles (Table 1-2). The PERMANOVA analysis found no evidence of differences in population structure in *P. argus* samples between BC and SK ($P = 0.139$) or evidence of an interaction between sizes classes between BC and SK ($P = 0.42$). These data suggested that patterns of genetic variation are similar between both MPA's confirming what was found in the regional analysis (see section 1.5.1), therefore this criteria was used to pool individuals from both locations into four size classes (Table 1-2) in the

search of pattern differentiations, and patterns among cohorts. Allelic richness ranged from 7.99 to 8.15 and the contribution of each size class to the total allelic richness varied from 1.17% to 1.13%. The *K*-means analysis suggested that clustering solutions with either two or three clusters generated the lowest BIC scores (Figure 1-13C). Both clustering solutions revealed the presence of 'low mixture' size classes that evoke cohorts.

The study by Truelove et al. (2011) then proceeded with the three-cluster solution, since this allowed for a greater amount of mixing among size classes parting from the premise that previous population genetics studies of *P. argus* suggested this species has high levels of gene flow (Silberman et al. 1994) and mixing among subpopulations (Naro-Maciel et al. 2011). The DAPC method revealed a clear genetic separation between the three clusters identified by *K*-means clustering (Figure 1-13D). The AMOVA analysis suggested evidence of population structure among individuals and between size classes. Pairwise comparisons of genetic differentiation (G_{ST}) between size classes found significant levels of differentiation among size class 90 to 100 mm and all other size classes. The DAPC analysis of mean membership probabilities provided evidence of population structuring (Table 1-2). Individual lobsters within size class 80 to 90 mm were predominately assigned to Cluster 1 and Cluster 2. In contrast, lobsters in size class 90 to 100mm were predominately assigned to cluster 2 (mean membership probability = 0.62). The highest levels of admixture were found in size class 100 to 110mm where lobsters were equally assigned to all three clusters. The lowest levels of admixture were found in size class 110 to 120 mm where lobsters were predominately assigned to cluster 1 (mean membership probability = 0.71).

Table 1-2 From Truelove et al. (2015) Summary of size classes information of *P. argus* with number of samples (N), average observed heterozygosity (H_O), average expected heterozygosity (Truelove 2014), inbreeding coefficient (G_{IS}), loci suspected of containing null alleles (Null), allelic richness (A_R), contribution to total allelic richness (CTR%), and mean posterior membership probability to each cluster (Cluster 1- Cluster 3). Values in bold indicate a positive contribution to total allelic richness or mean posterior probabilities > 0.6 to one of the clusters.

| Size Class | N | H_O | H_S | G_{IS} | Null | A_R | CTR% | Cluster 1 | Cluster 2 | Cluster 3 |
|------------|-----|-------|-------|----------|------------------|-------|--------------|--------------|--------------|-----------|
| 80 to 90 | 42 | 0.614 | 0.691 | 0.113 | Par7 | 7.988 | -1.168 | 0.499 | 0.407 | 0.094 |
| 90 to 100 | 34 | 0.570 | 0.696 | 0.181 | Par2, Par7, Par9 | 8.396 | 1.127 | 0.321 | 0.620 | 0.059 |
| 100 to 110 | 42 | 0.604 | 0.693 | 0.128 | Par7 | 8.044 | -0.039 | 0.361 | 0.401 | 0.239 |
| 110 to 120 | 22 | 0.591 | 0.690 | 0.144 | Par7 | 8.154 | 1.074 | 0.707 | 0.200 | 0.092 |

A valued aspect of the study by Truelove et al. (2015) is that it identified significant levels of genetic variation between four carapace length size classes of *P. argus* inhabiting the two geographically isolated MPA's in Mexico BC and SK. Microsatellite analysis showed variation between size classes, consisting of changes in levels of genetic differentiation, probability of assignment to genetically unique clusters, and in total contribution to allelic richness. The two size classes that contained the highest levels of allelic richness and total contribution to allelic richness (size class 90 to 100 mm and size class 110 to 120 mm) were also predominantly assigned to cluster 2 and cluster 1 respectively, which suggests that the same analysis should be carried out at the regional level by including all MPA's sampled in the study by (Truelove et al. 2014) (reviewed in 1.5.1), in order to confirm the same level of connectivity with MPA's found further south.

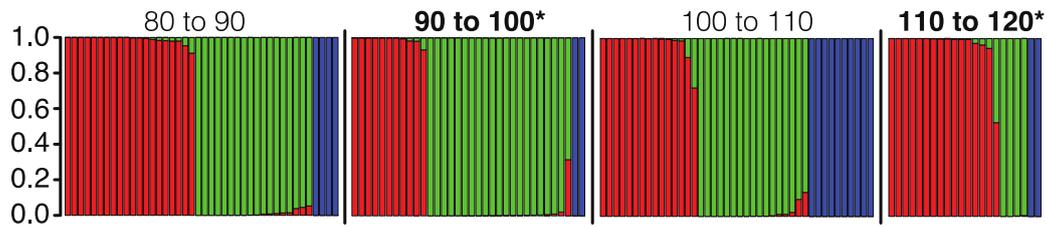


Figure 1-14: From Truelove et al. (2015): Membership probabilities for individual spiny lobsters from discrete size classes belonging to genetically unique clusters. Each vertical bar represents an individual spiny lobster and is divided into colour segments that are proportional to the probability of belonging to a genetically unique cluster (red = cluster 1, green = cluster 2, and blue = cluster 3). Each discrete size class is displayed at the top of the figure and the black vertical line separates each size class. Size classes displayed in **bold** with an asterisk (*) have > 60% of individuals belonging to a single genetic cluster. The scale bar for the probability of assignment to each cluster is located to the left-hand side of the figure. The order of individuals within each size class was sorted by assignment probabilities to each cluster. The number of genetically unique clusters was determined using *K*-means clustering, and assignment probabilities for each cluster were calculated using discriminant analysis of principle components.

Defining corresponding size classes for outlining possible age structures and describing potential cohorts for the SK and BC *P. argus* populations is restricted because of a number of knowledge gaps in the local populations. For example, variables that may help define the local length/age relationships such as growth rates and moulting frequency measured *in situ*, as well as natural mortality and recruitment parameters estimated locally are either not publically available or not up to date for BC and SK (Lozano-Álvarez et al. 1991b, Maxwell et al. 2007, Sosa-Cordero et al. 2008, Ramírez-Estévez et al. 2010). Given this, in the study by Truelove et al. (2015) the age groups for SK and BC were established in a semi-arbitrarily way by diving these into distinct cohorts every 10mm. This decision was thought to have implications in the analysis and results, and that the size classes evaluated as independent categories may have consisted of several age groups, depending on how growth, mortality, moulting frequency and other similar variables act upon different stages of development (lengths and size) of the lobsters sampled in each of the size classes which were evaluated.

As mentioned by Truelove et al. (2015) data from spiny lobster growth and size at maturity estimates suggest that the size classes of lobsters that were sampled from BC and SK MPAs most likely recruited to these MPAs during different time periods of settlement, as temporal variation among the genotypes of new puerulus recruits may have explained these results (Selkoe et al. 2006). Biophysical modelling studies of *P. argus* larval dispersal concur with the findings, as independent biophysical modelling studies on larval recruitment dynamics suggest that spiny lobster populations in Mexico are highly dependent on larval recruitment from distant source populations, as described by (Briones-Fourzán et al. 2008, Hunt et al. 2009, Butler et al. 2011). Variation among the genotypes of individual *P. argus* lobsters that recruit from various source populations may explain the high levels of variation observed between the sizes classes, the fact that total contribution to allelic richness varies between size classes and in some cases may be negative (e.g. size classes 80 to 90 mm and 100 to 110 mm). Negative contributions to diversity have been explained by the diversity of the immigrant population being lower than the mean total diversity or because the population is well mixed and not divergent (Petit et al. 2008). The *K*-means clustering analysis suggests that the latter case is the most likely since size classes 80 to 90 mm and 100 to 110 mm manifested the highest levels of mixing among all clusters.

Findings from the study by Truelove et al. (2015) reveal the usefulness of collecting size data from each individual lobster to improve the interpretation of population genetic analyses and evidences genetic connectivity at a local level between SK and BC, confirming the possibility of commonly shared genetic pool between MPA's at a regional level (Truelove et al. 2014). The latter has revealed the possibility that cohorts differentiate into genetic clusters, implying temporal variation among the genotypes of larval recruits (Selkoe et al. 2006, (Larson & Julian 1999, Kennington et al. 2013).

Knowledge produced in the genetic studies in SK and BC from both regional and local perspectives (Truelove et al. 2014, Truelove et al. 2015) suggest that an international and regional approach for sustainable fisheries is best for guaranteeing the recruitment of pueruli inputs. However, the fact that there was a positive spatial autocorrelation and genetic variance showed that the SK population was more differentiated from spiny lobsters in all other MPAs (including BC) (Truelove et al. 2014), could imply that populations do not completely depend upon the same sources of larval input, and/or that a certain level of self-recruitment may occur. This and other relevant issues framed within a management context of the SK and BC fisheries are further discussed in sections 9.2.1 and 9.2.2 of this thesis.

1.6 Characteristics of the lobster *Panulirus argus* fisheries in the Mesoamerican Barrier Reef System (MBRS)

Understanding and managing the MBRS as an ecosystem (Arceo et al. 1997, Muhling et al. 2013) which withstands ecological interactions of multiple species, held to very particular oceanographic dynamics (Ezer et al. 2005). The fisheries complexity per se (Seijo 2007), is then made more complex by the fact that it extends through four political borders (Mexico, Belize, Guatemala and Honduras) (see Figure 1-1) where fishers frequently trespass, due to lack of international vigilance or trans-boundary control systems at sea. The socio-political context only adds to the complexity of sourcing regional standardized data bases, which are accountable for fishery evaluation within the MBRS region. This is particularly true for *P. argus* lobster fisheries, where high demand and value have encouraged illegal fishing, which goes unreported in the official catch volumes (i.e. (FAO, 2011)

Establishing fishery management boundaries based on the existing political frontiers (municipalities, states, and countries) is the current practical approach towards management in the MBRS. As commented in previous sections, multiple studies suggest that the larval source and sink populations of *P. argus* lobsters may originate and be linked to extensions beyond the MBRS, further north, south and west in the Caribbean (Diniz et al. 2005 , Briones-Fourzán et al. 2008, Butler et al. 2011, Truelove 2014), (Chávez & Ley-Cooper 2007, Ehrhardt et al. 2010b, Naro-Maciel et al. 2011). Therefore a fishery approach to management based on political borders may not be the most effective tool from a biological stand point, but possibly the only alternative for governance and enforcement of existing legislation. Lobster stock estimates within the MBRS are extremely vague, as knowledge gaps are increased by the fact that the current management boundaries and fishing concession areas are not established using bio-geographic criteria or oceanographic knowledge, but rather with reference to political borders. Management of fisheries is a complex process that requires the integration of resource biology and ecology with economic and institutional factors affecting the behaviour of both fisher and politicians (Caddy & Seijo 2005). Agreements on conjunctive management plans could be a positive objective of the political process in the MBRS, in relation to fisheries.

The wide distribution of many countries in the MBRS and the wider Caribbean, make the spiny lobster *P. argus* commercially valuable and ecologically important per se (Lipcius & Cobb 1994). The different phases of the *P. argus* life cycle represent a critical link in the

marine food web in each of its different habitats throughout its ontogenetic development, from the open ocean to coastal habitats. Besides serving as prey for nurse sharks, octopus, finfish and other marine species, the *P. argus* also serves as a key predator for a diverse assemblage of benthic and infaunal species, and its selective predation can cause profound effects on species composition and size-frequency distributions of invertebrates such as sea urchins, mussels and gastropods (Lipcius & Cobb 1994, Muñoz-Núñez & Crowder 2009, Lavalli & Spanier 2010, Briones-Fourzán & Lozano-Álvarez 2013). In this section of the thesis, regional processes to be considered in an ecosystem approach to fisheries management are identified and include environmental and ecological features, as well as species behaviour and lobster population dynamics related to fisheries. However, further details are revised and discussed throughout the different chapters and sections, where specific aspects for *P. argus* in BC and SK biosphere reserves were reviewed within a regional context.

As one of the most high-priced luxury seafood items in the United States, Europe, and Asia, spiny lobsters are valued not only as a food source, but also as a source of revenue and as a source of recreational and aesthetic value in many countries (Lipcius & Cobb 1994, Rudd 2001). The highest market prices are found in Asia (Ley-Cooper 2009, Jain & Garderet 2011). Although *P. argus* lobsters support some of the largest commercial fisheries in the Caribbean, many are concurrently sustained by small-scale artisanal fisheries, which differ considerably from industrial operations, in terms of the management arrangements and practices (Butler 2001, Seijo 2007, Ehrhardt et al. 2010b). Out of all the fished resources of the region, this species is the one with the highest value in the market, and the main source of income for many coastal communities (Puga et al. 2005, Roheim 2008, Cinner et al. 2009, Ley-Cooper & Chávez 2009, Gardner et al. 2013) and arguably the case in most Central American communities which fish on the MBRS (Seijo 2007), and definitely for SK and BC..

Although there are gaps concerning information on FAO statistics on the landings throughout these regions (Phillips 2013), according to FAO (2011), the region considered as the greater Caribbean is the greatest producer of spiny lobsters (*Panulirus* spp) as Latin America and the Caribbean represent approximately 56% of the total production. According to in Phillips et al. (2013) all *Panulirus* commercial fisheries are considered fully exploited, and total landings for *P. argus* were estimated to be 31,638 t, where the highest volumes are known to be from Bahamas [7,138 t], Cuba [4124 t], Brazil [≈7000 t], Nicaragua [ND], USA [1827 t], Honduras [ND], and Mexico [469 t], (as presented in table 10.1 and figure 10.7. of the book by Phillips et al. (2013)

As pointed out more than two decades ago (Phillips et al. 1994), the trend towards high demand and market prices has continued to intensify fishing pressure on spiny lobster populations. This has required innovations in management strategies in order to regulate pressure, in many cases attempting to improve the situation without having the data required to backup decisions regarding control of fishing exploitation. Nevertheless landings for *P. argus* had already reached their peak during the 1987-1997 decade, at about 32 to 37 metric tons, with a landed value of about US\$300 million, which decreased by about 55% in the 2000's and increased again in the last decade mainly due to the Bahamas fishery (Ehrhardt et al. 2010b, FAO 2011, Phillips et al. 2013). Along with exploitation, changes in environmental and ecological conditions are likely to be impacting spiny lobster habitat in the Gulf of Batabanó in Cuba (Puga et al. 2008). High demand and low supply of spiny lobster has driven most fisheries to an excess of fishing capacity and caused overfishing in most fisheries, where the last 10 year recruitment patterns have followed decreasing catch trends in most fisheries (Chavez 2007, Ehrhardt et al. 2010b, Phillips 2013).

Strategies and arrangements for managing lobster fisheries in different countries vary widely, although most attempt similar regulations such as establishing a minimum lobster size, implementing spawning season closures and the prohibition on fishing berried females (Seijo 2007, Ríos-Lara et al. 2012, Gardner et al. 2013). Socio political problems including corruption, lack of governance, and lack of financial resources for vigilance, are problems which are not exclusive to fisheries in Mexico and Central America. On top of this, the relative geographical isolation of many fishing areas including MPA's in the MBRS has resulted in the lack enforcement of these and other fishing management measures, or by all means any type of regulation in some areas.

Despite some valuable regional efforts such as the Mesoamerican-MAR/CARICOM meetings between fishers and managers, as well as holding expert FAO workshops which have been held (Arce et al. 2001), there is still not an integrated consensus regarding the establishment and implementation of management strategies in the MBRS. A few examples are: a) There are still variations in fishery season opening dates between bordering countries like Mexico and Belize, where illegal and unregistered conch and lobster trade is common along the southern Mexican border, especially during June which happens to be the last month of Mexican fisheries closed season, and the opening month for Belize fishing season; b) Some hookah based fisheries in Honduras and Mexico (excluding SK and BC) have great problems with decompression sickness and diver deaths caused by exceeding underwater

time limits for catching lobster and sea cucumber. Industrial boats which collect lobster from small fisheries move indistinctly between borders in Nicaragua and Honduras without providing any clarity as to where these landings should be reported; d) There are different criteria for measuring minimum size of lobsters with uncertainty concerning tail (135 mm) and carapace length (≈ 78 mm CL) and conversions; e) Lack of control in landed lobsters, where egg bearing females are castrated (unhatched eggs and spermatophores are removed) before commercial handling at the docks (Ley-Cooper, unpublished data).

Some of the previously mentioned gaps in regulation, along with illegal fishing make regional management a complicated task for the MBRS. As listed by Caddy and Seijo (2005) there is a series of key issues associated with non-sustainability that cause difficulties in stock management and recovery which are common to most fisheries, and especially but particularly apply to the MBRS: “(i) Overcapacity of fleets; (ii) Increasing demand, and prices for fish on global markets; (iii) Political disagreement concerning assessment of fleet overcapacity; (iv) Lack of political will to take necessary actions to restore stocks; (v) Lack of implementation of the precautionary approach; (vi) Short memories by stakeholders of what is a ‘recovered’ or ‘normal’ fish stock; (vii) Problems between parties sharing resources in deciding on allocations (or on shares of total fishing capacity); (viii) Inadequate funding of Commissions and the unwillingness of member States to cede management control to them; (ix) Absence of a management or recovery plan agreed to by all parties leads to weak or conflictual management strategies; (x) Inadequate links between government and industry promotes illegal fishing and evasion of regulations, because the rationale for regulations has not been explained to industry; (xi) ‘Top-down’ governmental decision-making ignores co-management with the fishing industry, but is proving unsuccessful in achieving consensus within the industry; (xii) Co-management is more effective, but time consuming. ‘rights-based’ approaches as ITQs, or community-based quotas, enable coastal communities to decide management strategies for inshore/local resources. (xiii) There is a need to monitor stock status by indicators not only in terms of biomass and exploitation rate, but also with reference to environmental/ecosystem change or regime shift”.

Increased and uncontrolled fishing is probably the greatest issue in the MBRS, as fishery licences and concessions are not adequately controlled nor frequently updated in the national databases throughout most of the region, as evidenced in some regional project reports by conservation agencies working in Honduras (USAID-CAFTA-WWF 2010). However, local initiatives to control fishing are being implemented in a number of countries,

defining no take areas and establishing biological reference points in SK & BC-Mexico (MRAG-Americas 2013), Guatemala and Honduras (USAID-CAFTA-WWF 2010). A proposal for fixed fishing quotas (ITQs) by Belize Fisheries Department in conjunction with NGO's like Environmental Defence Fund, The Nature Conservancy-TNC and WWF in Belize is also ongoing (see www.edf.org and wwf.org, the Natural Capital Project). The effects of many of these marine resource conservation and fishery management initiatives are yet to be appreciated and assessed, as most goals are envisioned in the long term, and many will need at least five years before they become effective, as for the MSC certification in BC and SK (MRAG-Americas 2013). The establishment of MPA's in SK and BC in the Mexican MBRS have now been in place long enough (INE-SEMARNAP 2000), for their effects on fisheries and their general management strategy to be evaluated, hence the importance of this study.

1.6.1 Mexico: Yucatán Península & Quintana Roo.

The *P. argus* fishery concentrated in the States of Quintana Roo. and Yucatán historically produced around 98.1% of the total catch of *P. argus* in the country, comprising 80% of the mean total catch produced in Quintana Roo (Lozano-Álvarez et al. 1991b). Recent numbers derived from total catch data (landings) reported by the fishing cooperatives and compiled by the Fisheries Department have been published in the *Yucatan Peninsula Management Plan for P. argus Lobster* (Ríos-Lara et al. 2012), indicating that changes have occurred and the total catch is reported to be around 0.48% in Yucatan and 52% in Quintana Roo, attributed mainly due to an increased effort along the coasts of the Yucatan and an evident decrease in Quintana Roo as from the late 1980's as observed in Figure 1-15.

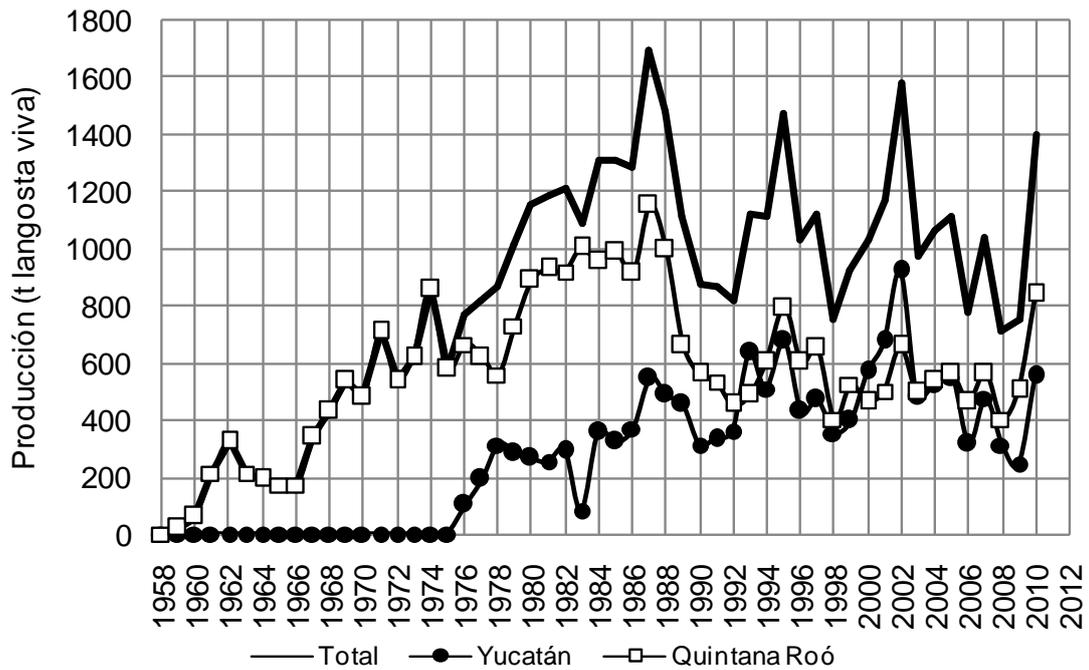


Figure 1-15 From Ríos-Lara et al. (2012), graph and data from Yucatan Peninsula *Panulirus argus* lobster Management Program the historical production of *P. argus* lobster (whole weight); The graph shows on the “Y” axis, live lobster landings tons (t), from the States of Yucatán (black dots) and Quintana Roo (white squares), and total catch (continuous black line) from 1958 up to the 2010 fishing season “X” axis.

The current organizational structure of the fisheries in Mexico, in the States of Yucatan and Quintana Roo is described in

Table 1-3. These consist of 4 Federations, 3 and 1 in each State respectively, 38 fishing Cooperatives, 19 in each State. These also include the number of fishers registered as permanent cooperative associates (total 1484; 856 in Yucatan and 628 in Q. R.), plus seasonally contracted fishers (total of 4,452; 2,568 in Yucatan and 1884 in Q. R.), as well as number of boats (963 small boats, and 42 bigger boats). Each cooperative has its own independent administrative structure, managed by a directive council that is composed of a president, secretary, treasurer and vigilance members, who are elected by all the associates. The administrative councils are in charge of administrating and managing all matters regarding financial and business aspects, permits, concessions and everything to do with relationships with authorities. See (Appendix 12.1).

Table 1-3: Organizational status of fishery composition in the states of Yucatan and Quintana Roo., for the lobster *P. argus* fishery. Source from Ríos-Lara et al. (2012).

| State | Fishing Federations | Fishing Cooperatives (Sociedades cooperativas) | Permanent Cooperative associates | Seasonal contracted fishers | Lobster fishing boats |
|---------------|---------------------|--|----------------------------------|-----------------------------|---|
| Yucatan | 3 | 19 | 856 | 2568 | 511 small boats 35 mayor (Nursing boats which can take up to 100 traps each) |
| Quintana Roo. | 1 | 19 | 628 | 1884 | 452 small boats 7 larger boats (nursing) |
| Total | 4 | 38 | 1 484 | 4 452 | 963 small boats 42 larger boats |

Spiny lobster fishing along the Mexican Caribbean coast (Yucatan and Quintana Roo) is based on a variety of fishing gears and methods, including traps, nets, SCUBA, hookah, skin diving and artificial shelters called *casitas cubanas* or *sombras cubanas* (Ríos-Lara et al. 2012) or simply *casitas* (Briones-Fourzán et al. 2000), described in greater detail in section 1.6.4.1.1. The use of standard surplus yield models and fishery assessments in general has historically been complicated in these fisheries, as there is ample variety in fishing gear, great diversity in management and cooperative arrangements, hampering standardization of data from fisheries and defining units of effort (Lozano-Álvarez et al. 1991b). Generally large knowledge gaps exist in relation to basic data indicating temporal effort variations and catch trends, data on population dynamics (i.e. movement and migration patterns)(Ley-Cooper et al. 2014), and biological aspects. Prompt evaluation of stock trends and sustainability aspects depends on this information, although the “Regional *Panulirus argus* Lobster Fisheries Management Plan” (Ríos-Lara et al. 2012), constitutes an important effort to document, assess, and propose general management rules for fisheries Yucatán Peninsula fisheries.

Studies carried out by academic institutions, NGO’s and government agencies, have been published as intermittent efforts to assess lobster population(s) in specific areas in order to evaluate sub-regional stock trends, as is the case in southern and central Q. R. (Arceo et al.

1997, González-Cano et al. 2000a, González-Cano et al. 2001, Sosa-Cordero et al. 2008, Ríos-Lara et al. 2012). However knowledge and data are still insufficient for carrying out standard fishery assessments, as catch alone is an inadequate indicator of abundance (Pauly et al. 2013), and certainly for sustainability. Studies (Ley-Cooper & Chávez 2009) and reports carried out by governmental (Ríos-Lara et al. 2012), and non-governmental organizations (Alvarez-Flores & Sosa-Cordero 2010), have been based on series of assumptions that use unknown biological parameters, and result in stock assessments with many output uncertainties. During the formal assessment process of the MSC certification of the SK and BC fisheries (MRAG-Americas 2012, 2013), participants and experts indicated that there is inherent difficulties for defining the boundaries of the stocks throughout the *P. argus* distribution area, as is certainly the case in Mexico (see further review and discussion in section 9.3.1.1.1). This is caused by lack of knowledge concerning population structure, larval origins and adult connectivity levels (Truelove et al. 2014). For this reason, environmental authorities such as CONANP CONABIO (see appendix 12.1) have searched for alternatives to establish preventative strategies and management measures like product ecolabelling (Ley-Cooper & Quintanar-Guadarrama 2010, Ward & Phillips 2013), together with local management programs in BC (Alvarez-Flores & Sosa-Cordero 2010) and SK Biosphere Reserves, in the southern and central portion of Quintana Roo..

The initial increase and post-decline pattern for catches following a peak in the late 1980's, has been reported by many authors (Briones-Fourzán et al. 1997, Sosa-Cordero et al. 1999, Sosa-Cordero 2003, Sosa-Cordero et al. 2008), and is a common tendency observed in most fisheries. These were progressively subjected to high levels of exploitation and have reached their maximum sustainable yields (Hilborn & Walters 1992, Seijo 2007, Pauly et al. 2013). Apparently this is the case in Q. R. as average catches have not recovered to levels originally observed before 1989 (CONAPESCA-SAGARPA 2013),(Ríos-Lara et al. 2012). During the decades of the 1990's and 2000's, catches in the intervening years have fluctuated around lower levels, showing relative stability and even slight indications of increments perceived among some populations such as BC and SK (Sosa-Cordero et al. 2008, Alvarez-Flores & Sosa-Cordero 2010, Ríos-Lara et al. 2012, Ley-Cooper et al. 2014).

Declines have coincided with periods in which Hurricanes such as Gilbert struck the coast of Quintana Roo., crossing the Yucatan Peninsula in September 1988, followed by Wilma in 2005 and Dean in 2007, destroying an enormous amount of fishing gear, which probably disrupted lobster population structure (Guzmán-Escalante 2010) in a way similar to

that of Cuba (Puga et al. 2013). Hurricanes have affected lobster's natural habitat ranging from seagrass, algae and mangroves used by puerulus for settlement, to coral structures and sea floor refuge for juveniles and adults, and also fishing gear like artificial shelters (casitas) (Beltrán-Torres et al. 2003, Ley-Cooper 2013), which provide refuge for lobsters (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán & Lozano-Álvarez 2013). Evidence for this has been documented with a reported reduction in catch immediately after the hurricanes struck in the south, Banco Chinchorro (Alvarez-Flores & Sosa-Cordero 2010) and the Bay of Espiritu Santo (Guzmán-Escalante 2010, Ley-Cooper et al. 2013). As published for Cuba, hurricanes may partially explain the reduced catch reported in Mexico, attributed to habitat loss, lack of recruitment, increased mortality, and lack of lobster abundance in shallow areas because refuge has diminished and weather conditions have obliged lobsters to move into deeper areas (Puga et al. 2013). As habitat in a various areas recovers from the effects of hurricanes and artificial shelter/casitas are replaced, fishers claim to have observed an increase in abundance, yet catch per unit of effort (CPUE) in certain areas such as BC and the BES and BA bays in SK have fluctuated around the same levels throughout the past two decades (Sosa-Cordero E. et al. 2008, Alvarez-Flores & Sosa-Cordero 2010, Ríos-Lara et al. 2012, Ley-Cooper et al. 2013).

1.6.1.1.1 Overview of lobster fishery management and applicable government legislation

An appendix (Section 12), lists definitions used throughout this section and the rest of this thesis, including names of management authorities and institutions, acronyms, as well as description of Norms and legislation which apply to Mexican Lobster Fisheries and MPA's. The agency responsible for fishery management, monitoring and enforcement is the National Commission of Aquaculture and Fisheries (CONAPESCA) (see appendix for further details). The general governance and management structure for lobster fisheries exploited in Mexico, applies to all species and is regulated by decree in the Mexican Official Norm (NORM-006-PESC-1993) this NORM was modified in sections 3.4 y 3.5 in 1995, 1997 and 1998. Regulations encompass management of the *P. argus* species in the Mexican Caribbean and Gulf of Mexico It is advantageous for the Mexican government and authorities to manage fisheries in a sustainable manner by applying existing legislation and enforcing good fishing practices. There are many laws, norms and regulations which deal with fisheries management, which are further described in the appendix.

In meetings held with fishery stakeholders such as the State lobster committee, authorities have publicly revealed that the number of inspectors and vigilance staff from CONAPESCA (approximately six for the entire State of Q. R.) are insufficient for checking every operation throughout the State, including vessels and chain of custody of fished products. However, other authorities linked to the Secretariat for Environment (SEMARNAT, PROFEPA, and CONANAP) also have faculties for enforcing and managing all fished resources, if these are extracted within a Marine Protected Area, National Park, or Biosphere Reserve. They can enforce environmental laws applicable to natural resources (i.e. LEGEPA, and Article 27 of the National Constitution). The highest ranking instrument, in the Mexican fisheries legislation is the Federal Fishery Law (Ley General de Pesca Sustentable y Acuacultura), which outlines general guidelines for fishery regulation.

The complexity of the legal framework, its limitations, and the scope of action of the different authorities make fishing management in MPA's a complicated task, even though hypothetically natural resources should benefit from more legal protection than elsewhere along the coast. The management system for Mexican fisheries in general, and for the SK and BC *P. argus* fisheries in particular are well defined on paper, however they are not always practically functional because hierarchical formation prohibit actions necessary for regulating illegal fishing activities. Various authorities are relatively ineffective at diminishing illegal fishing within an MPA, as they always depend upon the presence of a colleague from other governmental departments when apprehending or fining illegal fishers. For example a park ranger from CONANP must act in Conjunction with an agent from PROFEPA and often accompanied by an armed Marine soldier, as well as a local police officer, in order to corroborate an act of illegal fishing and take action to apprehend and/or fine the illegal fishers. Many times lack of institutional coordination prevents legal charges from proceeding and leaves authorities in a powerless position when enforcing the law.

The BC and SK Biosphere Reserves are benefitted by a legal framework that enforces regulations at both local and Federal levels, whereas other coastal areas that not defined as MPA's lack this. Additional measures include internal regulations implemented by cooperatives that choose to include and apply rules as resulting from general assembly agreements, or from the MPA's management plans and regulations; actually the most effective in isolated communities such as Punta Allen (Sosa-Cordero et al. 2008), (Seijo & Fuentes 1989).

As the *P. argus* lobster fishery in BC and SK are based on fishing rights and concessions allocated to fishers who are members of cooperatives, this ensures legal compliance in a socially structured management arrangement. The fishery stakeholders in SK and BC take great responsibility due to awareness of the privilege their exclusive fishing rights within an MPA represent, motivating their compliance with the legal framework established by the Biosphere Reserve management rules and programs (Ley-Cooper 2010).

1.6.1.1.2 Fishing gears

The main target species for fishers in Quintana Roo Mexico is lobsters, although during the lobster fishing season should bad weather conditions with water turbidity prevail, thus limiting operations and freediving for lobsters, target species may be replaced by snapper, groupers, and others fished with hand held lines. In this State, particularly around the upper central section starting from Tulum (Figure 1-2 and Figure 1-6) towards the north (Isla Mujeres and Hol Box) lobster fishing methods include traps, scuba, hookah and skin diving with no defined depth limits (Arceo et al. 1997, Ríos-Lara et al. 2012). In addition, during the autumn winter migration from October to December lobster tangle nets are used near Isla Contoy located between Cancun and Isla Mujeres North Q. R. (González-Cano 1991).

The central and southern portions of the State are discussed in the next section (1.6.2), as in SK and BC lobsters are fished using particular management systems that vary from the rest of the State; at shallow depths (< 20 m) by free diving. In SK, lobsters are almost entirely harvested from casitas (see definitions in section 1.6.4.1.1) with either hand nets (jamos) or snare loops (Ley-Cooper et al. 2013).

In parts of Northern Quintana Roo which includes Isla Mujeres, Cancun and Contoy area, fisheries are regulated by the corresponding authorities (see section 1.6.1.1.1) and the existing norms apply (see section 12.1), In spite of this there currently seem to be more fishing cooperatives, associated fishers and lobster traps than the fishery can sustain as financially self-sufficient and sustainable in the long term, as catches continue to drop and are lower than those reported in past decades (González-Cano 1991, González-Cano et al. 2000b, Ríos-Lara et al. 2012).

In the Central (i.e.SK) and southern (i.e. BC) portion of the State the situation is quite different to the North, and varies between each of the registered cooperatives (Table 12-1). The trend is that catches have been relatively stable, and effort is limited in general terms by

the number of fishers and restricted by the number of small boats that are allowed in the MPA's (Ley-Cooper 2006, Ley-Cooper & Chávez 2009).

Trends towards overcapitalizing the fisheries in Q. R. with excess gear and infrastructure mostly seems to have occurred in the late 1980's as a result of the lobster fisheries boom which registered record catches in this State, when sustainability did not seem to be an important issue (González-Cano et al. 2000b). Since then, landing volumes and income have apparently reduced in the North, while remaining stable in the Central-Southern portion of the State, thus self-regulating this overcapitalizing trend, making it clear that investment and commercial operations need to be balanced out by the revenue derived from fishing (Ley-Cooper, 2010). The Vigia Chico fishing cooperative based in Punta Allen north of SK has intuitively learnt to balance revenue and investment when replacing their main fishing gear-casitas, whilst driving fishing operations towards a maximum economic yield based on financial controls and an exemplary administration related to its organizational structure (Sosa-Cordero et al. 2008). A financial crisis suffered in the late 80's, when the cooperative carried a huge debt caused by partially subsidized, but excessive investment in infrastructure and fishing gear later wiped out by Hurricane Gilbert resulted in this adjustment. Currently government subsidies depend on evidence of productivity levels before co-investment in fishing gear and equipment, and cooperatives mostly pay independently for their boats, motors and fishing gears, and this in turn is limited by the income and available capital that fishers are able to access (Arceo et al. 1997, Sosa-Cordero 2003, Sosa-Cordero E. et al. 2008, Ramírez-Estévez et al. 2010{González-Cano, 2000 #37, Ríos-Lara et al. 2012).

1.6.2 Mexico, Quintana Roo., Central and Southern management

Zones/Units:

The fisheries in the Mexican Caribbean coast of Q. R have been described in a comprehensive manner by several authors (Arceo et al. 1997, González-Cano et al. 2000b) (Lozano-Álvarez 1994, Ríos-Lara et al. 2012). The local fishery aspect by (Seijo & Fuentes 1989, Lozano-Álvarez et al. 1991b) and a more recent review by (Sosa-Cordero et al. 2008) have set a good framework for analysing fisheries based in the **Central and Southern Zones** of Q. R.

Some of the most recent efforts for local stock assessments in the South-Central Q. R fisheries besides those carried out in this thesis (for details see chapters 0 and 6 (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014)); were focused on the BA/Punta Allen Fishery in SK

(Sosa-Cordero et al. 2008) in BC (Alvarez-Flores & Sosa-Cordero 2010), and there is currently one in process (Sosa-Cordero 2014). The latter have adopted the conceptual framework developed by (Charles 2001), recognizing that a fishery system possesses three components: (a) natural, (b) human and (c) management; where the human component consists of fishers, their fleet and fishing gear, as well as special gear in fishing communities. This thesis is inspired partially by those criteria as well as those established as principles in the MSC (Marine Stewardship Council 2010, MRAG-Americas 2012)

Most previous and recent studies carried out in the State of Q. R., which include a stock assessment component, divide the zone into three traditional fishing zones, identified as the: **“Norte”-North, “Centro”-Central and “Sur”-South**, originally defined according to physical habitat characteristics and “development” levels (Miller 1982). Up to now, these are management units as recognized and used by the INAPESCA/CONAPESCA, fishing authorities. Figure 1-16, shows the units based on details presented in Table 1-4, Table 1-5, and Table 1-6. The original source is the Lobster *Panulirus argus* Management Program of the Yucatan Peninsula (Ríos-Lara et al. 2012).

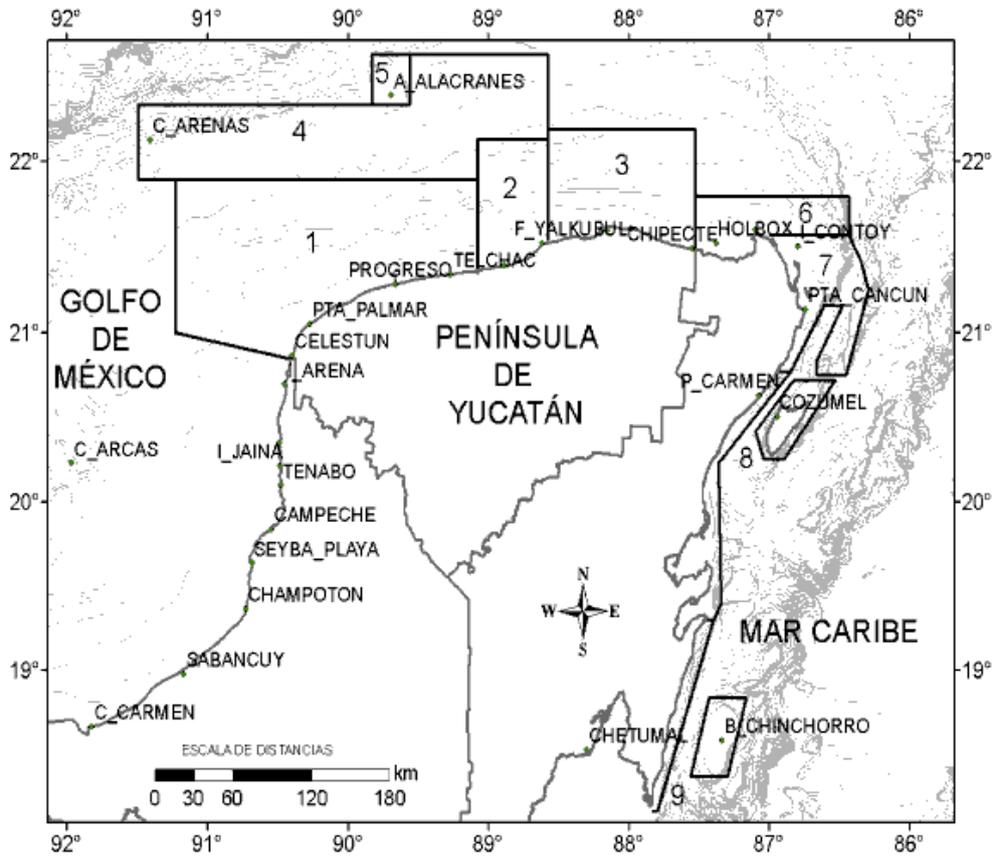


Figure 1-16 From: Ríos-Lara et al. (2012) Map of the Yucatan Peninsula and coast of Quintana Roo showing the management units/Zones as are assigned by the management authorities: Poniente (1) Centro de Yucatán (2), Oriente (3), Zona Profunda (4), Alacranes (5), Norte (6), Noreste (7), Centro de Quintana Roo-“Centre” (8), and Sur-“South” (9). (Note Zones 8 and 9 correspond to the Central (SK) and Southern (BC) Zones respectively).

Table 1-4 From Ríos-Lara et al. (2012): Number of fishing cooperative associates, bigger and minor fleets which catch lobster in the coasts central and Southern Coast of Quintana Roo. (Source: Sub-delegaciones de Pesca-SAGARPA and Sociedades Cooperativas Q. R., 2012). (Note those shaded in dark grey are the cooperatives that work in SK and light grey in BC)

| Fishing Cooperatives (Sociedades Cooperativas de Produccion Pesquera-SCPP) | Associates | Minor boats | Mayor Boats | Motors | Fishing Zone/Management area |
|--|-------------|-------------|-------------|------------|------------------------------|
| Pescadores de Puerto Morelos | 9 | 11 | | 11 | Central "Centro" |
| Cozumel | 46 | 25 | | 25 | Central "Centro" |
| Pescadores de Tulum | 21 | 16 | | 16 | Central "Centro" |
| Pescadores de Vigía Chico | 76 | 55 | | 55 | Central "Centro" |
| José María Azcorra | 22 | 18 | | 18 | Southern "Sur" |
| Langosteros del Caribe | 28 | 8 | 1 | 8 | Southern "Sur" |
| Andrés Quintana Roo. | 23 | 11 | 1 | 1 | Southern "Sur" |
| Pescadores de Banco Chinchorro | 33 | 13 | 1 | 13 | Southern "Sur" |
| Total in Centro Q. R. | 152 | 107 | 0 | | Central "Centro" |
| Total in southern "sur" Q. R. | 84 | 50 | 3 | | Southern "Sur" |
| Total in Quintana Roo. | 628 | 452 | 7 | 442 | |
| Total in Yucatan Peninsula | 1484 | 963 | 42 | 958 | |

According to the "Carta Nacional Pesquera" (see terms and definitions in section 12.1), based on the stock assessments and population diagnostics of Ríos-Lara et al. (2012), the fishing effort should no longer increase in the whole Yucatan Peninsula, including the Central and Southern Zones of Q. R. Yet, despite of these recommendations the ongoing changes and development of the fisheries throughout the whole region continues, and there are a large un-estimated number of illegal boats /fishers which catch lobster without licences, permits or hold concessions (Ríos-Lara et al. 2012).

1.6.2.1.1 Central Zone -“Centro” fishing management Unit 8

The Central Zone management Unit “Centro” of Q. R. (8) can be seen in Figure 1-16, and is described in Table 1-5. I review some considerations regarding the appropriateness of the structure of these units both from a geographical and social perspective.

Table 1-5 from Ríos-Lara et al. (2012). Coordinates which correspond to the Central Zone as assigned management authorities (Ríos-Lara et al. 2012)

| | |
|---|---|
| <p>Central Zone management Unit “Centro” Q. R. (8): The management unit includes the bays known as Bahías de la Ascensión, Espíritu Santo in the Sian Ka’an Biosphere Reserve, as well as the coast of Tulum, Puerto Morelos and the Island of Cozumel</p> | <p>Coast: 20.76° N, 86.85° W; 20.77° N, 86.95° W; 20.22° N 87.36° W; 19.39° N, 87.35° W; 19.29° N, 87.39° W; 19.29° N 87.46° W.</p> <p>Isla Cozumel: 20.72° N 86.83° W; 20.72° N 86.53° W; 20.25° N 86.9° W; 20.24° N 87.04° W; 20.42° N 87.1° W.</p> |
|---|---|

Along the entire coast of the Yucatan Peninsula, and most evidently in the State of Q. R., many cities such as Cancun, Playa del Carmen and Tulum manifest some of the fastest growing human population rates and coastal urban developments in Mexico and the Caribbean Region (Origlio et al. 2014). Likewise, the level of “development” of fisheries, compared to that described three decades ago (Miller 1982), has undergone changes in terms of size of fleet, type of boats, fishing gear and technology, as fishing areas have diversified or expanded throughout the peninsula (Ríos-Lara et al. 2012). As described extensively in sections 1.6.3 and 0, the so called “development” of fisheries within SK and BC Biosphere Reserves has been substantially different in many aspects, compared to other fisheries based further north. Fisheries included in the so called “Central Zone” management unit, which extend to urbanized areas like Tulum, Cozumel and Puerto Morelos manifest social, ecological, environmental and management details in these fisheries, which are hardly comparable to SK and BC. The urban population on the reef and coastal environment where local lobster populations are harboured in SK obviously has much less impact than occurs in the northern fisheries of Puerto Morelos and Tulum, even though they are categorized under the same management unit.

Table 1-4 and Table 12-1, show that all six cooperatives that have concessions and fish in the SK and BC Biosphere Reserves, stand within the categories of that currently referred to as Central and Southern Zone fisheries, which also happen to include cooperatives known as Pescadores de Puerto Morelos (PPM) and Pescadores de Tulum (PT). Although there are established Marine Parks within the vicinity of Puerto Morelos and Tulum, there are evident differences in the fishing gear used in the PPM and PT cooperatives. The latter are allowed to fish using SCUBA, hookah and gaffs, and management arrangements for fishery concessions are notably different to those found in the SK and BC Biosphere Reserves (see sections 0 and 1.6.3). Both concessions assigned to PT and PPM cooperatives extend along the coast from the north of Q. R. close to Cancun (Punta Maroma), to the south in Tulum, bordering with the concession held by the cooperative Vigia Chico in SK as evident in (Figure 1-7). Except for the landings registered and reported by the two official cooperatives PT and PPM (Ríos-Lara et al. 2012), in the northern section of the so called “Central Zone” management unit, it is publicly known that many non-commercial landings are scarcely monitored and illegal fishing is common in areas which are open to free divers and tourists, so that catch numbers are unknown.

The island of Cozumel opposite Playa del Carmen is also considered within the Central Zone, and it is where the “SCPP-Cozumel” local cooperative offices are based, which fishes the local lobster stock. Lobsters fished from the island of Cozumel are internally differentiated from those fished in SK, in terms of cooperative administrative purposes, as lobster from “Las Radass” are fished using tanks and hookah from the deep reefs (10 -30 m), in and around the island. As stated, the SCPP-Cozumel also holds the exclusive concession for fishing within the SK Biosphere Reserve in the southern bay known as Bahía del Espíritu Santo-BES (Figure 1-8), with controlled access. resulting in a very different fishery than that on Cozumel island, as SCUBA and hookah are prohibited, and most lobsters are harvested from casitas (see section 1.6.4.1.1 **Casitas:**) (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). Both areas: Cozumel Island and BES in SK, as members of SCCP-Cozumel cooperative report their landings to INAPESCA/CONAPESCA

Total catches for the Central Zone management unit “Centro” include landings obtained by cooperatives from PT, PPM, Cozumel and Vigia Chico. The cooperative Vigia Chico that fishes the northern bay (BA) of the SK Biosphere Reserve catches 16% of total catches for the entire State, and clearly dominates the Central management Unit (Sosa-Cordero et al. 2008). Notably, the Central Zone unit includes the landings from the

cooperative SCPP-Cozumel as one component, although ideally this should be divided into two separate components, one from one from catches in BES-SK (Figure 1-8), and the other from Las Radas in Cozumel Island, which are geographically separated and most probably comprise independent stocks (Lozano-Álvarez, 2003, Ley-Cooper, 2014).

The landings reported from lobster fished within the bay of BES-SK are wrongly divided into two cooperatives, pertaining to different management units: 1) landings from the SCPP-Cozumel which fishes the northern side of the BES Bay (Figure 1-8), considered part of the landings from the Central Zone management Unit; and 2) the landings from the southern part of BES (Figure 1-9) from the cooperative José María Azcorra-JMA, which are considered as part of the landings pertaining to the Southern Zone management unit, as seen in Table 1-6 and further discussed in the following section. .

1.6.2.1.2 Southern Zone -“Sur”, Fishing management Unit 9

The area defined as **Southern Zone -“Sur”, Fishing management Unit 9** can be seen in Figure 1-16, and is described in Table 1-6 as has been published in the Lobster *P. argus* fishery Management Plan for the Yucatan Peninsula (Ríos-Lara et al. 2012). Some considerations are reviewed and discussed regarding the structure of this unit both from a geographical and social perspective in the following paragraphs.

Table 1-6 shows the latitudes and longitudes which correspond to the Southern Zone management Unit as are assigned by the management authorities INAPESCA/CONAPESCA (Ríos-Lara et al. 2012)

| | |
|--|---|
| <p>Southern Zone Management Unit “Sur” (9): Banco Chinchorro Biosphere (BC)</p> | <p>Banco Chinchorro: 18.83 N, 87.43 W; 18.83 N, 87.17 W; 18.36 N, 87.30 W; 18.36 N, 87.57 W Coast: 19.30° N, 87.40° W; 19.30° N, 87.46° W; 18.21° N, 87.78° W; 18.21° N, 87.842° W</p> |
|--|---|

As mentioned, the borderline between central and southern management units is arbitrary and effectively crosses the middle of the Bay-Bahía del Espíritu Santo (BES) found in the south of the SK Biosphere Reserve. This means that landings reported from the fishery occurring within the BES are erroneously separated into the different management units 1) landings from the SCPP-Cozumel which fishes the northern side of the Bay (Figure 1-8), are

considered as landings from the Central Zone management Unit; and 2) landings from the cooperative José María Azcorra-JMA, which effectively fish the southern side of the BES (Figure 1-9), are considered as part of the landings of the Southern Zone management unit. This results in landings from JMA being added to catches from the Banco Chinchorro, Xcalak and Mahahual areas, which include concessions and permits related to three other cooperatives, Pescadores de Banco Chinchorro, Langosteros del Caribe and Andres Quintana Roo (Table 1-4), together constituting the total landings for the Southern Unit.

From a biological stand point, it seems inappropriate to separate BES into two independent Central and Southern management units, as a considerable number of lobsters move indiscriminately in and around the BES bay between both cooperative concession areas, as well as towards the deeper areas (>20 m), implying a single stock within the BES (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). There is also a certain level of exchange between the bays of BA and BES within the SK Biosphere Reserve, indicated by lobsters tagged in the North BA, later recaptured in the southern BES (Lozano-Álvarez et al. 1991b, Ley-Cooper et al. 2013). The separation of BES lobster landings into southern and central units refers only to administrative practical criterion that is useful for CONAPESCA, as catches are reported by two independent cooperatives (Cozumel and JMA), yet the division of the BES lobster stock hardly makes sense in terms of local population dynamics (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). This will be further discussed in section 1.6.3 Mexico- Sian Ka'an and Banco Chinchorro Lobster Fisher.

There is an additional socio-environmental error in the current definition of the southern management unit, as it combines catches from the Cooperative JMA in BES-SK, with landings received from the other three cooperatives based in the south (Table 1-4), which operate in Mahahual Xcalak and Banco Chinchorro-BC areas. In this management unit, the bulk of the catches of the three other cooperatives are mainly fished in the BC. The fact that BC is geographically situated 30 km to the east, with a 1000 m deep channel separating it from the coast (see section 0), raises the question of whether these lobster populations currently pertaining to the southern unit are interconnected in any way. As lobsters can move large distances for many reasons (Herrnkind et al. 1973, Bertelsen 2013), it would be plausible to hypothesize that populations from Xcalak and Mahahual in the south are linked by adult migrations towards SK in the north, although no corroborating evidence exists to date. As the 1000 m deep channel represents a geographical barrier for migrating lobsters, a similar hypothesis assuming walking migration to connect adults from BC with the

coastal juvenile and adult lobster populations of Mahahual, Xcalak, or SK is negated (Ley-Cooper 2006). However, this does not negate possible connectivity by larval recruitment (Briones-Fourzán et al. 2008), evidenced by a shared gene pool, indicating that these and other lobster populations may originate from common source populations found elsewhere within the MBRS (Truelove 2014, Truelove et al. 2015).

More current knowledge on the stocks dynamics, as well as ecological and environmental factors which affect the *P. argus* populations and could help to define these fisheries boundaries better (Sosa-Cordero 2003, Ley-Cooper et al. 2013(Sosa-Cordero, 2008 #114). The BES Bay is only divided by a virtual border line which distinguishes the casitas and Campos which are located within the given fishing concessions which belong to each of the fishers and the cooperatives that fish in this bay, yet the tagging studies have shown that lobsters move irrespective of this and may be marked in one concession area and recaptured in the other (Ley-Cooper et al. 2013).

A redefinition of the central and southern portion of Q. Roo is required from a regional fishing management perspective. Establishing the size and boundaries of the units is not easy, but application of new criteria and data analysis from a multidisciplinary perspective for incorporation into future evaluations is to be commended (Bellchamers 2009, Bellchamers et al. 2012, de Lestang et al. 2012, Bellchamers et al. 2014). A bank-by-bank approach for local stock assessments seems more appropriate, as the different fishing areas become confused within each of the larger management units, and can't be differentiated. The SK and BC currently considered as “units of certification” enables these populations to be assessed as independent stock units, regardless of levels of larval connectivity. In very general terms, stock status for SK and BC can be assessed by reference to standing benthic population(s), (ranging from the juveniles that have settled to the large adults); apparently more indicative of local population dynamics (MRAG-Americas 2013),(Ley-Cooper et al. 2013),(Ley-Cooper et al. 2014).

1.6.2.1.3 SK and BC within the MPA Management Scheme:

Marine protected areas may provide an alternative for recovery of overexploited spiny lobster populations, by permanently closing fishing or spawning grounds, or proclaiming areas in which fishing mortality is restricted (Buxton et al. 1999, Walters 2000, Bevacqua et al. 2010, Groeneveld et al. 2013), as is the case of both the Sian Ka'an (SK) and Banco

Chinchorro (BC) Biosphere Reserves which have limited access/entry, and fishing effort is restricted as exclusive concession rights are only allowed to six fishing cooperatives (see details 1.6.3. to 0.).

These BR were officially declared as marine protected areas in 1986 (SK) and 1996 (BC), and MPA management programs have been published (INE-SEMARNAP 2000, CONANP 2007), acknowledging the historical rights of the community based cooperatives, that have been widely recognized for their harvesting techniques and social arrangements (Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, FAO 2001, Sosa-Cordero E. et al. 2008, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013). Unlike many national parks and protected areas elsewhere, the SK and BC Biosphere Reserves (BR), permit scientific research, human habitation and regulated use of natural resources/fishing (López & Consejo 1986, INE-SEMARNAP 2000, CONANP 2007, Ríos-Lara et al. 2012). Founded mainly for conservation purposes, the overarching goal of the MPA's/BR management and strategic planning has been to develop a sustainable ecosystem, which also fulfils the needs of local stakeholders and inhabitants.

1.6.3 Mexico- Sian Ka'an and Banco Chinchorro Lobster Fisheries

Besides the fact that eco-tourism is developing fast, the *P argus* fishery is still the most important socio-economic activity in the BC and SK MPA's (Jain & Garderet 2011, Velez 2014). Unlike other parts of the State, fishery catches in both areas of the BC & SK have been relatively stable in terms of total landings and catch rates throughout the last two decades (Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007). Total tail weight (TW) catches have varied around 20t TW for BC; and 70t TW total catch for Northern SK-BA; and 30t TW total catch for Southern SK-BES, which equate to approximately one third of total whole weight (WW) catch values. Yearly ranges in weight are from 5-10 t (TW) in BC and 15-30 t (WW) in SK respectively, depending on the year evaluated (CONAPESCA-SAGARPA 2013), and the length weight conversion values used for transforming data from TW to WW (Lozano-Álvarez et al. 1991b, Sosa-Cordero 2003, Sosa-Cordero et al. 2008, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010, Ramírez-Estévez et al. 2010, Ríos-Lara et al. 2012, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Sosa-Cordero 2014).

General fisheries management arrangements for the Yucatan Peninsula have developed a series Fishery management arrangements for the Yucatan Peninsula have commonly

introduced a series of regulations aimed to improve the management of lobster stocks by control of effort. Cooperatives are awarded a 20 year fishing concession, that implies an obligatory annual check-up of associates with obligatory licence renewal (section 1.6.1 and Annex) (López & Consejo 1986 , Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998, Ríos-Lara et al. 2012). Apart from compliance with general rules applicable to the entire Q. R. State, enforcement of the Federal fishery and environmental legislation is also carried out by local environmental authorities (CONANP and PROFEPA), who are assigned to each of the SK and BC MPA's, as are the fisher-cooperative related park management arrangements (INE-SEMARNAP 2000, CONANP 2007).

In BC and SK, conservation and management goals of the environmental and fishing authorities coincide in promoting rational exploitation of fished stocks, aiming at sustainability in order to obtain maximum long term socioeconomic benefits (INE-SEMARNAP 2000), (CONANP 2007 , Ríos-Lara et al. 2012). In SK finfish fly fishing activities are progressively gaining importance, but have not surpassed the *P. argus* fisheries, and in BC *P. argus* has historically represented more than 70% of the total fishing income for all three cooperatives (Ley-Cooper 2006). This has recently increased as reef finfish species are only targeted by spear fishing and handheld lines during *P. argus* closed season, and conch (*Strombus gigas*) fishing has been completely suspended for a 5 year period as from 2010.

In both areas, artisanal fishers only fish by skin diving without the help of any compressed air source such as SCUBA and hookah are prohibited. This limits the capacity of fishers to a maximum depth of 20m approximately; confining the catch of *P. argus* mainly to shallow areas such as the lagoon in BC and the BES and BA bays in SK, where natural habitats and artificial refuge/casitas are found at depths of less than <20 m (Lozano-Álvarez et al. 1991b, Sosa-Cordero 2003, Ley-Cooper 2006, Ley-Cooper & Chávez 2009, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). Size composition and abundance of catch, also varies according to fishing method employed, as well as depth and fishing area surveyed (Lozano-Álvarez et al. 1991b, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998, Sosa-Cordero et al. 1999, Ley-Cooper 2006, Briones-Fourzán et al. 2007). In the bays of SK the 20 m depth limit of the fishery enables a portion of the population to escape being fished (Lozano-Álvarez et al. 1993, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), which is also likely to occur in BC (Ley-Cooper 2006). This implies that in BC most of the lobsters are caught within the lagoon and shallow areas (< 20 m) with high exploitation rates, and only

the shallow portion of the stock is subject to being assessed when using fishery dependent/catch data (Sosa-Cordero 2003, Alvarez-Flores & Sosa-Cordero 2010).

Commercial catch records and some fishery independent surveys have been the main source of data available to determine exploitation of fished lobster stocks in the Mexican Caribbean, and in particular in the BC (González-Cano et al. 2001, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010), and SK (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 1998, Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). Budget restrictions and a lack of formal protocol that integrates all interested stakeholders (Fletcher 2005), has historically hindered consistent monitoring and systematic data collection in the BC and SK fisheries, causing many gaps in the existing historical catch and effort data series, although some recent conservation projects have been providing new data (Ley-Cooper 2009, Sosa-Cordero 2014). Many local lobster population evaluations and stock assessments have had to assume population and biological parameters based on estimates from other fisheries, which in some cases has resulted in disparate results when estimating exploitation rates and fishing mortality (González-Cano et al. 2001, Ley-Cooper 2006, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010).

A time schedule program has now largely been agreed upon by most stakeholders in order to accomplish the urgent need for necessary research to regularly monitor the lobster population to be conducted with yearly assessment of stock status, as recommended by the ongoing MSC certification program (MRAG-Americas 2012, 2013). Up-to-date stock status evaluation is required to assess the current situation in these fisheries, determine biological reference points, reduce uncertainty in bio-economic benchmarks (Puga et al. 2005, Penn et al. 2015), and consequently improve the management of these fisheries. Unfortunately, funding sources and institutional support for these studies are lacking.

As in most other Caribbean areas, *P. argus* fishery (Ehrhardt et al. 2010a), catches have tended to decline from the 1960's, primarily attributed to high exploitation rates of local stocks (Lozano-Álvarez 1994, Sosa-Cordero 2003, Sosa-Cordero et al. 2008) and factors affecting pueruli recruitment, which appear to depend on multiple source populations (Briones-Fourzán et al. 2008, Butler et al. 2011, Truelove et al. 2014). Adequate management requires an evolutionary approach with biological controls as a precursor to input-based controls thus enabling the capture of sufficient fishery-based data and resulting in effective management decisions (Penn et al. 2015). Assessing local lobster population parameters,

catch rates and recruitment patterns is crucial for good management, and these must be evaluated on a regular basis to reduce uncertainty regarding the status of fisheries (de Lestang et al. 2012). These evaluations may be used for constructing bio-economic reference points and for assessing and explaining fishery trends for improved management (Seijo & Caddy 2000, Seijo 2007, Donohue et al. 2010).

Many biological factors and population parameters, necessary for modelling the population's dynamics and assessing lobster stock status remain unknown in the *P. argus* fisheries of BC and SK. Knowledge related to puerulus settlement and juvenile recruitment levels is lacking in many fisheries (Butler et al. 2008), (Briones-Fourzán et al. 2008), as are natural mortality and survival rates among different age groups (Arce et al. 2001),(Puga et al. 2013), ecosystem and population connectivity levels and genetic structure of the lobster population stocks (see section 1.5) (Wright et al. 2006, Ehrhardt et al. 2010a, Truelove 2014, Truelove et al. 2015), just to mention a few.

Information gaps have been revealed when attempting to estimate exploitation rates and fishing mortalities in BC, applying varied methodological approaches (MRAG-Americas 2012, 2013).Lack of clarity concerning input variables such as recruitment and other population parameters has resulted in contrastingly different results emerging from a) fishery simulation models which have identified the risk of overexploitation by comparing with levels prior to the 1960's (Ley-Cooper & Chávez 2009) and b) other methods of stock assessment which have declared no overexploitation risk (González-Cano et al. 2001, Alvarez-Flores & Sosa-Cordero 2010). It is now more obvious that spatial analysis is required to estimate mortality rates (Harford et al. 2015), requiring empirical data to statistically validate estimations and sustain modelling techniques (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Penn et al. 2015)

1.6.4 Mexico-Sian Ka'an (SK)

Section 1.2, reviews details from the Sian Ka'an Biosphere Reserve *P. argus* fisheries, located in Q. Roo Mexico (Figure 1-6) within the bays Bahia de la Ascension (BA) in the north (Figure 1-7) and Bahia del Espiritu Santo (BES) (Figure 1-8and Figure 1-9) in the south. The Yucatan Peninsula Lobster Management Plan (Ríos-Lara et al. 2012) currently defines these as comprising part of the central and southern stock, respectively (see 1.6.2.1.1and 1.6.2.1.2).

Although fishing efficiency is likely to have improved in SK due to the introduction of four stroke boat motors and GPS technology in recent years, catches have apparently remained relatively stable, without any apparent increase in effort in terms of number of fisherman or boats. Details in terms of estimated catch per unit effort (CPUE), (Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013) are thoroughly reviewed and discussed in chapters 0, 6 and 7.

In SK, *P. argus* lobsters are fished by skin diving down to casitas (see section 1.6.4.1.1) in exclusive access areas called Campos (see section 1.6.4.1.1) and hand harvested using hand nets and snares in the inner reefs at limited depths (< 20 m) (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013),(Ley-Cooper et al. 2014).

As stressed in many studies carried out by many authors throughout passed years (Seijo & Fuentes 1989, Lozano-Álvarez et al. 1991b, Lozano-Álvarez et al. 1993, Arce et al. 1997, Sosa-Cordero et al. 1998, Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007, Seijo 2007, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013) the casitas and campo plots administered by the cooperatives in SK constitute a harvest technique which is quite unique in terms of property arrangements, as virtually the entire sea floor is divided into a series of concessions, signifying individual territorial ownership and ensuring improved management of corresponding resources. Individual fishing property rights related to fixed areas throughout the “Campos” enable cooperative vigilance, where park ranger and fishing authorities administrate the fishery in a co-management arrangement.

1.6.4.1.1 Casitas:

Casitas also known as “pesqueros” in Cuba, are a special type of large (1.5-2 m² in surface area) but low lying (8-15 cm in entrance height) artificial shelters used to commercially harvest full-sized *P. argus* lobsters that take refuge within (Lozano-Álvarez et al. , Cruz & Phillips 2000),Sosa-Cordero *et al.* 2008(Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1999, Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2013, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). These may vary in shapes and sizes, and a few different commercially viable models used in both bays within SK are presented in Figure 1-17 and Figure 1-20, which were drawn in 2010 by (Guzmán-Escalante 2010). Smaller versions (e.g. 1 m² in surface area and 4 cm in entrance height) have also been used experimentally (Sosa-Cordero et al. 1998, Briones-Fourzán et al. 2007, Ramírez-Estévez et al. 2010, Gutzler et al. 2015).

Casitas were first used in Cuba, then in Mexico and more recently in the Bahamas (Baisre 2000), Cruz & Phillips 2000,(Deleveaux & Bethel 2002),(Lozano-Álvarez et al. 1991b, Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007, Ehrhardt et al. 2010a, Briones-Fourzán & Lozano-Álvarez 2013, Gutzler et al. 2015). In Mexico, casitas are extensively used in the two large bays that form part of the SK, BA and BES (Figure 1-6, Figure 1-7, Figure 1-8 and Figure 1-9). The use of casitas is the most common fishing gear used in these bays since the late 1960's, and in more recent years their use has expanded to other parts of the coast (Briones-Fourzán et al. 2007). Several casita designs have been identified and documented in SK, but the most commonly used are those shown in models 1, 2 3 and 6 presented in Figure 1-17 to Figure 1-20 (Guzmán-Escalante 2010). The main standard measurements that prevail in the most common commercially used casitas have the average surface area of (1.5-2 m²) with entrance size of (8-15 cm in entrance height), characteristics which help enhance production, for details see (chapter 4) and publications by (Briones-Fourzán et al. 2007) and (Briones-Fourzán & Lozano-Álvarez 2013).

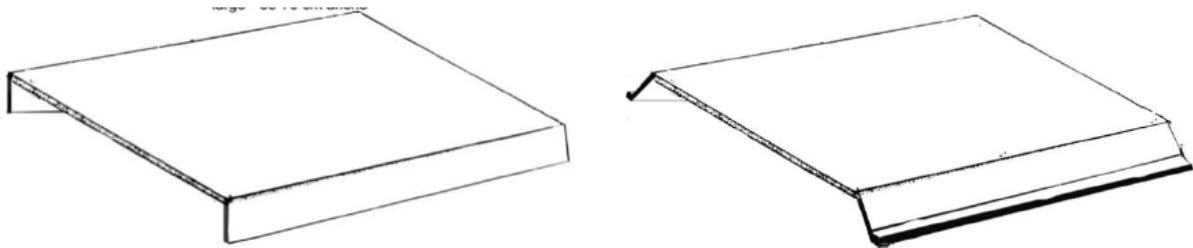


Figure 1-17: From Guzmán-Escalante (2010)casitas/artificial reefs model 1 and 2. The left model (1) is most probably the most popular, where the cement plank placed in a rectangular arrangement may vary in measurements between (1.20 to 1.40 m) in length to (0.85- 0.70 m) width, with entrance heights of around 0.08-0.15 m, and side lifting boards of equal height; entrances are at both ends. The right hand model (2) has similar dimensions to model 1 with two entrances, but sides tilted at approximately a 45° angle, with a small lip at the bottom, as this is mainly used on muddy surfaces.

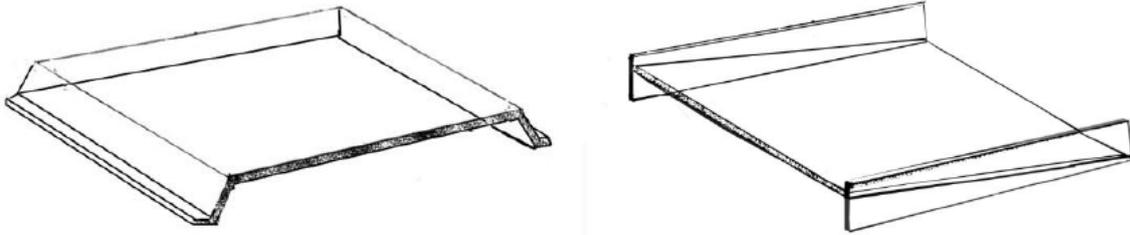


Figure 1-18: From Guzmán-Escalante (2010)casitas/artificial reefs model 3 and 4. The left model (3) is amongst the most popular, where the cement plank placed in a rectangular arrangement may vary in measurements between (1.20 to 1.40 m) lengths to (0.85- 0.70 m) widths, and heights of the entrance(s) around 0.10-0.15 m, with equivalent size on the side lifting boards. It has similar dimensions to model 2 except it has only one entrance instead of 2, where the 3 sides are tilted in approximately in a 45° angle with a small lip at the bottom, as it is normally used on muddy surfaces. The right hand model (2) has similar dimensions as model 1 except it has two entrances, where the sides are inclined in approximately in a 45° angle, with a small lip at the bottom, as it is normally used on muddy surfaces. The right hand side model (4) is called “caguamo doble” which only consists of two sided boards which support the cement plank of similar dimensions as the above, yet it is tilted and allows for only one entrance for lobsters. This one is used in areas where dolphins commonly tip casitas over

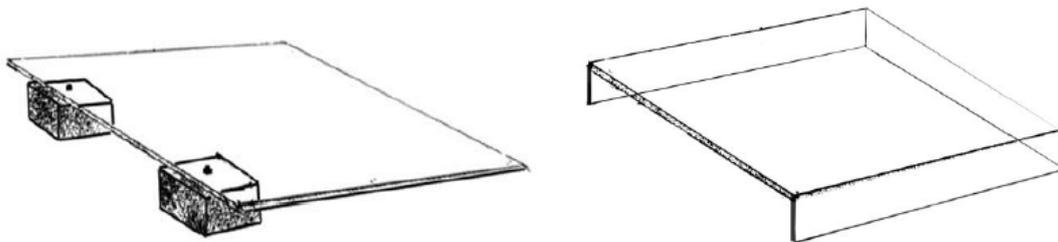


Figure 1-19 From Guzmán-Escalante (2010) casitas/artificial reefs model 5 and 6. The left model (5) simply consist of cement plank measuring 1.20 by 1.10 m in a rectangular arrangement, lifted by 2 cement blocks bolted on to the plank and are amongst the least popular in SK. The right hand model (6) also named “Caguamos” are a completely covered cement plank with a series of 3 sided upholding cement boards with only one entrance.

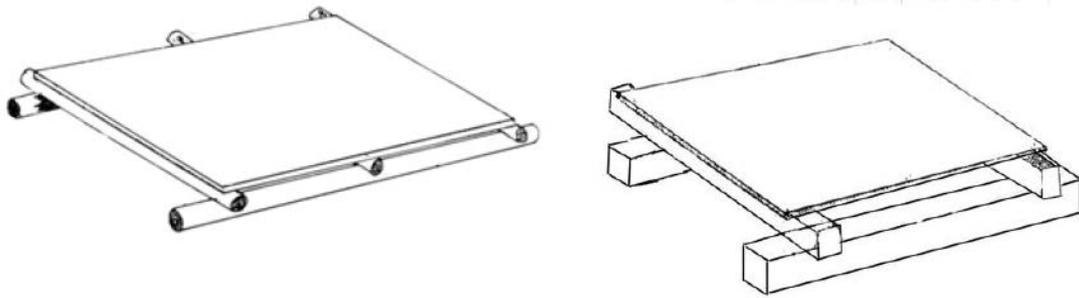


Figure 1-20: From Guzmán-Escalante (2010) casitas/artificial reefs model 7 and 8, are the probably the least popular as materials Chit Palm (*Thrinax radiata*) are now protected by environmental legislation. These simply consist of a set of chit logs (left), or wooden beams (right) measuring 1.20 by 1.10 m in a rectangular arrangement covered by a cement plank.

In Mexico-SK, the fishers fish for lobsters lifting the casitas and extract the lobsters that occupy these by using diving masks and snorkels, by skin diving with loops and hand held nets “Jamo”. The use of gaffs in the southern bay of BES has been completely substituted with loops for catching lobsters alive, and seine nets are no longer popular (Ley-Cooper et al. 2014). Internal cooperative regulations forbid fishing in someone else’s casitas and campo. On average, there are 3.3 casitas/ha in individual Campos (See next section) with distances between casitas varying from 25 m to over 50 m (Briones-Fourzán et al. 2007, Ley-Cooper et al. 2011, Briones-Fourzán & Lozano-Álvarez).

When this study began, casitas had not previously been implemented in BC, except for a study conducted between 2005 and 2007, where 56 experimental casitas were deployed in the atoll lagoon, for the main purpose of studying growth, movements, and prevalence of *P. argus* lobsters with the PaV1 disease, where 1060 lobsters ≥ 20 mm carapace length (CL) were tagged and 404 (38%) recaptured (Ramírez-Estévez et al. 2010). Since 2010, a few experimental trials and provisional studies have been conducted aimed at promoting the use of casitas in BC, but using wooden models instead of concrete design for the trials. These will be further discussed in Chapter 4 (Ley-Cooper et al. 2011).

A review of casitas and the controversy over their use was undertaken by Briones-Fourzán and Lozano-Álvarez (2013) with discussion focussing on how the use of these structures may simply attract lobsters already in the system (“attraction” hypothesis), thus increasing their vulnerability to predators, including humans as recently suggested by Gutzler et al. (2015) or actually increase production of lobster biomass (“production” or “enhancement” hypothesis), thus increasing their potential impact on components in the

benthic ecosystem, as previously acknowledged by Briones-Fourzán et al. (2007). Some of the potential benefits are derived from the introduction of casitas as reported by Briones-Fourzán and Lozano-Álvarez (2013), which include: (a) casitas increase survival of lobsters because they allow for cohabitation of small juveniles, which are more vulnerable to predation, with larger conspecifics that offer greater individual and collective defensive abilities (Briones-Fourzán et al. 2007), (b) casitas allow lobsters to exploit the available food resources in a more efficient way, reducing the time they are exposed to predators, (c) because casitas are deployed far from the coral reefs, their use reduces impact of fishers on the reefs and on the large reproductive adults that dwell in these habitats, and (d) casitas promote selectivity in terms of lobster size and maturity. Besides this casitas enable lobsters to be harvested and sold alive, which adds considerable quality/freshness and economic value to the fished product, while decreasing investment costs for storage and refrigeration, thus reducing the need to increase fishing effort to increase income (Ley-Cooper & Garcia-Rivas 2009, Jain & Garderet 2011).

Experiments and studies regarding the use of casitas in locations other than Mexico and Cuba, have questioned their potential for enhancing spiny lobsters, suggesting that casitas in nursery areas may serve more as an attractor than as an enhancer, by increasing juvenile mortality and vulnerability to predators, thus serving as “ecological death traps” (Butler & Herrnkind 1997),(Gutzler et al. 2015). These studies implement other casita than those used in SK, and use invasive tethering methods for assessing “natural mortality” so that juveniles become vulnerable to predators when translocated from one casita to another; likewise in these areas there is a tendency for mismanagement related to casita use provoking local opposition from fishers who fail to respect regulations, as many installed casitas that are not controlled (Ehrhardt et al. 2010a) The environmental impact of casitas in many sites has not been extensively assessed (Briones-Fourzán & Lozano-Álvarez 2013), for example (Ehrhardt et al. 2010a) reported that in Bahamas there are more than 700,000 casitas that are never retrieved from the fishing grounds but are replaced at a rate of 20% per year, causing probable but not definitive negative effects, as Bahamas reports the highest landings in the Caribbean according to FAO statistics (Phillips et al. 2013).

Briones-Fourzán and Lozano-Álvarez (2013) present at least four reasons why casitas should probably not be used to enhance any habitat in any location: 1) These structures may serve as tropical ontogenetic shifters but not for habitat specialist lobsters, 2) they should probably not be used in tropical coastal areas where natural crevices abound, 3) they should

probably not be used in subtropical/temperate areas where changes in density of the local *Panulirus* species might result in trophic cascades that could alter prey communities and 4) Perhaps most importantly, even in the case of a tropical species such as *P. argus*, it is paramount that environmental impacts of extensive deployment should be properly monitored or controlled, as otherwise any production benefit might be quickly offset. As pointed out by Briones-Fourzán and Lozano-Álvarez (2013) the production benefit achieved by large scale casita style fishery production as in Cuba (with 200-300 thousand casitas in operation) (Puga et al. 2008) and with the smaller scale casita based fishery in Mexico (20,000 casitas), success has largely been due to proper management of fishing and environmental impacts, with limited fishery catches, where ownership of casitas is warranted and fishers comply with local regulations. Casitas are arranged in a certain way (3.3 casitas ha⁻¹) probably decreasing their impact on seagrasses (Briones-Fourzán & Lozano-Álvarez 2013, Puga et al. 2013). In any case introducing casitas seems to go hand in hand with the introduction of a well-managed campo system, which allows for semi-ownership of the seafloor (see next section), and self-surveillance, which improves vigilance by park rangers and fishers who mostly cooperate with carry out security checks (Briones-Fourzán & Lozano-Álvarez 2001a) (Seijo 2007, Sosa-Cordero et al. 2008).

1.6.4.1.2 Campos:

In the central coast of Q. R. in Bahía de la Ascensión (BA) and Bahía Espíritu Santo (BES), which form part of the Sian Ka'an Biosphere Reserve (SK), local fishers have divided the bays into a number of individual marine parcels '*campos*' (see Figure 1-7 BA, Figure 1-8 BES north, and Figure 1-9 BES south), so that the sea floor is virtually divided into a series of concession blocks allocated to individuals or families. This ensures better management of the resources within them. These Campos fall within larger areas which constitute the renewable fishing concession, which was granted by the Federal government for 20 years to a handful of people with reference to certain historical territorial rights in the fishery. The campo plots administered by the cooperatives and in turn by the individual associated fishers, farmed using the distinctive harvest technique of the casitas mainly because of the designation of property (see Figure 1-7 BA, Figure 1-8 BES north, and Figure 1-9 BES south).

Fixed fishing areas, with designated individual fishing property rights throughout the "campos" result in a dispersed effort for harvesting lobsters both spatially and over time thus a tendency to rush towards increased abundance, as often occurs in other fisheries relying on

natural refuge sites such as BC, is reduced. The local fishing cooperatives have also developed a set of simple rules for their management which are regulated by self-surveillance and enforced by the cooperative members without need of intervention from external authorities (IMPI 2009, Ley-Cooper 2010, Briones-Fourzán & Lozano-Álvarez 2013(Sosa-Cordero et al. 2008),, Gardner et al. 2013).

1.6.5 Mexico-Banco Chinchorro (BC):

During the course of an eight month fishing season, the total catch of *P. argus* lobsters in BC fluctuates at around 25t(TW)/65t(WW) (CONAPESCA-SAGARPA 2013). Conservation initiatives are slowly trying to introduce ecotourism and diving as an alternative source of income to fishing, yet the *P. argus* fishery still represents the highest economically valued activity for the communities that have access to the BC Biosphere Reserve and own the exclusive concession rights to fish in this MPA. Fishing is restricted to the three licensed fishing cooperatives (Table 1-4) and lobster landings have been relatively stable over the last two decades (Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010, Ley-Cooper et al. 2011).

In BC technology has also improved throughout the years in terms of motor boat power and the use of GPS systems, and catches have also been achieved without an apparent increase in effort in terms of number of fishers or licenced boats (Ríos-Lara et al. 2012). Local environmental factors, patterns of recruitment, and growth of lobsters may have helped to sustain the current status of the stock (Lozano-Álvarez 1992, Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007, Alvarez-Flores & Sosa-Cordero 2010, Ley-Cooper et al. 2011).

Territorial rights granted to fishing cooperatives with exclusive access to the Biosphere Reserve in BC are somewhat similar to the SK case. This arrangement of co-management with the park authorities-CONANP, implies there is a semi-ownership of the marine resources in BC. Fishers associated with any of the three registered cooperatives (

Table 1-3), are allowed to operate freely throughout the entire atoll, although they mostly concentrate on the shallow reefs (< 20 m) and internal lagoon areas (Figure 1-3)(Ley-Cooper 2006). Unlike SK where each cooperative uses one portion of the coast (i.e. BA, BES-S and BES-N), fishers in BC have not subdivided the atoll into three independent

concession areas, although plans to install casitas and Campos are in place (see chapter 4)(Ley-Cooper et al. 2011).

Throughout the year, in addition to complying with all the rules and regulations enforced by the fisheries authorities, cooperatives work under close daily surveillance carried out by park authorities (Ley-Cooper 2006). Furthermore, the BC MPA's park authorities and fishing cooperatives meet periodically with an Advisory Council, composed of most fishery stakeholders and includes members of the research steering committee, academics and fishery experts who help carrying out assessments and suggest management measures (Ley-Cooper 2009, Ley-Cooper & Quintanar-Guadarrama 2010, Ley-Cooper et al. 2011). In both the SK and BC MPAS's the co-management arrangements and the fishing restrictions to control effort contrast to most open access fisheries which exist throughout the *P. argus* distribution range, as many are progressively being depleted and heading towards the so called "tragedy of the commons" (Hardin 1968) This is resulting from weak management arrangements and lack of effort control systems (Caddy & Seijo 2005, Gardner et al. 2013, Harford et al. 2015).

In response to being fished it is likely that throughout the years BC *P. argus* populations may have undergone many changes including reductions in total numbers/total biomass, changes in size frequency distributions, age structures and spatial distributions. As mentioned by Haddon (2001), fishery science uses mathematical and statistical descriptions of these processes as it attempts to understand the dynamics of exploited populations, assuming that if we can understand how populations respond to different perturbations then we should be able to manage the fisheries according to our chosen objectives.

Continuous research and standardized monitoring programs to assist in producing management measures occur in many lobster fisheries around the world (Bellchambers et al. 2009, Bellchambers et al. 2014), yet in BC and SK irregular monitoring efforts and sporadic research studies have resulted in gaps in relation to fishery data bases, and a lack of existing local information. Mostly limited by time and budget, this situation has led to divergent results when estimating fishing mortality (F), and exploitation rates (E) in BC. These and other fishing parameters have been calculated by using inconsistent and varied modelling methods and simulation techniques (González-Cano et al. 2001, Sosa-Cordero 2003, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010).

More than a decade ago fishery parameter estimates and exploitation rates were determined by depletion methods in BC indicating relative stability in the fisheries

(González-Cano et al. 2001, Sosa-Cordero 2003). Subsequently, fishery simulation model-FISMO (Chávez 2005) that was applied in 2009 to BC, produced several predictive scenarios for fishing mortalities “F” with plausible suggestions for achieving maximum sustainable yields (MSY); where most outputs predicted slight overexploitation rates, and recommended a reduction in effort in order to achieve optimal MSY levels in the near future (Ley-Cooper & Chávez 2009). In 2010, the fishery was again assessed, using an improved version of the depletion approach by (Sosa-Cordero 2003), which produced results showing that the fishery had stable status, with relatively low to moderate levels of exploitation (Alvarez-Flores & Sosa-Cordero 2010). Nearly half a decade has passed since the fishery simulation model FISMO (Chávez 2005) was used as an evaluation tool for carrying out a bio-economic assessment of the BC lobster fishery, which resulted in a publication by (Ley-Cooper & Chávez 2009) during the development of this thesis. Since then, the FISMO model and results have been scrutinized, reevaluated and discussed as part of the MSC certification pre-assessment and evaluation process with most stakeholders and experts participating on the part of the BC lobster fishery, which amongst other things has made evident the need for a critical analysis and update of information (MRAG-Americas 2012, 2013).

Authors of the different stock assessment studies carried out for BC (González-Cano et al. 2001, Sosa-Cordero 2003, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010), have publically recognized that the techniques used to evaluate the BC fishery have been based on very different methodological approaches, as each one used different statistical tools and computational programs to assess data (MRAG-Americas 2012, 2013). In all cases input referring to total catch data was basically obtained from the same sources, in the form of cooperative log books and fishery/CONAPESCA data files; yet many population input parameters were based upon hypothetical assumptions and information found from studies carried out elsewhere in Mexico or the Caribbean such as those by (Lozano-Álvarez et al. 1991b, Arce et al. 2001, de León et al. 2005) amongst others, as local information and empirical data for BC was scarcely available at the time (MRAG-Americas 2013). More recent efforts for assessing the stock are in progress (Ríos-Lara et al. 2012, Sosa-Cordero 2014), however preliminary results for 2014-2015 are yet to be formally evaluated and published.

The fact is that distinct stock assessments carried out using both simulation scenarios (i.e. FISMO: (Chávez 2005, Ley-Cooper & Chávez 2009), as well as multiple season depletion models (Alvarez-Flores & Sosa-Cordero 2010) are independent, not directly

comparable, and at different levels of complexity. Although fed with similar catch data, contradictions mainly thrive with regard to estimated exploitation levels, and are attributed to differences in multiple factors including: a) biometric data sets which were fed into the model(s), b) data processing techniques, equations and modelling programs used, c) dissimilar criteria in population input parameters that include factors such as recruitment, growth, length weight relationships, natural mortality, and d) distinct fishery parameters ranging from age of first catch, to effort, catchability and estimates of relative abundance. The latter differences in criteria applied by each of the authors are not yet a matter of consensus, as there has been no formal opportunity for researchers to gather all data into one unique database, or discuss and define these and other fishery parameters for BC (MRAG-Americas 2013).

Inclusive and structured workshop style meetings amongst experts to discuss these themes, where the central dialogue should be scientific evidence and evaluation of results, data processing methods and empirical knowledge based on experience working on the fishery would be recommendable for BC (Fletcher 2005, Bellchambers et al. 2014). These examples have highlighted the urgent need for consolidating expert research groups (Ríos-Lara et al. 2012, Bellchambers et al. 2014) which can produce, update and share one single comprehensive fishery dependent data base, whether they are produced from recent monitoring programs, government data sets, independent research or collaborative efforts for the BC fishery. Assessing the BC stock should be undertaken for the benefit of improving sustainability criteria, and implementing management strategies by means of well-informed stakeholders (Velez 2014). Regardless of which methodologies are chosen for assessing the stock, new information needs to be compiled and standardized in a peer reviewed process, and evaluations should at least be based on the same catch and effort data sets. Studies should preferably use similar population input parameters and criteria such as growth factors, natural mortality rates, recruitment, based on uniform biometric data. These are some basic necessary steps needed for any future assessments of the BC lobster fisheries status, where a qualitative risk assessment is the recommended process for achieving it (Fletcher 2005, Bellchambers et al. 2014).

Periodic re-examinations of stock assessment methodologies, and ground truthing of data and input criteria are expected to occur in every fishery that is willing to develop and implement sustainable management systems (Penn et al. 2015). It is a necessary to rigorously evaluate biological parameters, update the yearly gathered fishery data, and reassess the

population dynamics criteria used in previous evaluations, in order to review the BC fishery status objectively. Recent studies and knowledge of *P. argus*, new considerations of local populations, and novel criteria for management strategies in the BC fishery have recently been explored, and need to be considered when assessing the BC *P. argus* stock and population dynamics. A series of considerations and some examples of knowledge required for assessing the BC are presented in the following paragraphs:

I. Spatial assessments considering unfished areas need to be incorporated into tagging research studies and population modelling designs in BC, in order to assess how the deep (>20m) unfished areas may enhance the *P. argus* fishery (Ley-Cooper 2013, Ley-Cooper et al. 2014) and explore the implications of these results for applying management strategies. A study of this nature also needs to be carried out for BC fishery, as the 20 m depth limit imposed on skin diving also exists, and it is very likely that population dynamics, relative abundance, recruitment, movements and migration patterns are also affected by this factor (Goñi et al. 2010, Bertelsen 2013, Harford et al. 2015).

II) Age and size structure of the population coupled with spatial distribution should be considered in any stock assessment study for BC, as these factors most probably affect local population dynamics. BC is a semi-closed population where benthic juveniles and adult lobster migrations are constrained within the atoll limits (Ley-Cooper 2006), because of the surrounding 1000m deep channel, this acts as a physical barrier for displacement of adult lobsters (Jordán & Martín 1987, Ley-Cooper 2006). As skin diving fishers cannot reach beyond the 20m depth, and management rules prohibit diving with alternative air sources, previous studies have suggested that size structure within BC varies with depth; hence lobsters follow a size gradient increase from smaller juveniles to bigger adults as depth increases (Ley-Cooper 2006). This also occurs in SK where lobsters are larger in deeper areas (>20 m) than within the bays (<20 m) (Ley-Cooper et al. 2014). Thus when estimating stock-wide fishing mortality for *P. argus* lobsters in BC, considerations concerning spatial distribution and movements (Bertelsen 2013) between the deep (>20m) and shallow habitat areas (<20m) (Ley-Cooper 2006), (Acosta & Robertson 2003), cannot be underestimated as these may affect exploitation rates and estimates of fishing mortality (Ley-Cooper et al. 2013).

III) Stock assessment models also need to be developed while ascertaining that movement is not occurring between fished and unfished areas. Estimates of exploitation rates,

and fishing mortality can be significantly affected when considering spatial ecology factors such as differential habitat (Acosta & Robertson 2003), as well as other uncertainties related to lobster behaviour and ontogenic movements between different depths (Bertelsen 2013, Puga et al. 2013), (Ley-Cooper et al. 2014). These factors have not been considered by the models produced in BC, simply because at that time, no tagging experiments had yet been carried out which would help estimate the rate of abundance and flux between fished and unfished areas. As fishing depths are limited by those accessible to skin diving, lobsters found in unfished areas and deep zones (>20 m) are most probably subject to different fishing mortality rates than those found in the shallow lagoon (<20m). Because, the Fishing effort tends to concentrate on the shallow lagoon areas in BC, where costs of fishing are less, access to reef crevices and lobster refuges is easier. Thus exploitation rates are potentially highest in shallow bays in Sian Ka'an (Ley-Cooper et al. 2014), . The fact that fishing effort and fishing mortalities in shallow and deep areas are distinct should always be contemplated in future stock assessment models.

IV- Studies carried out in SK and BC on how the prevalence of the Pav1 virus may affect the juvenile sector of the population (Ramírez-Estévez et al. 2010, Candia-Zulbarán et al. 2012), should be replicated and updated in BC, as conditions may have changed considerably in the past five years. Improved understanding of how PaV1 affects *P. argus* movements, growth and juvenile mortality in BC, are factors that could be incorporated into the stock modelling assessments when estimating natural and fishing mortality levels for BC lobster population.

V.- Although presently evaluated as one single unit for purposes of the MSC certification assessments (MRAG-Americas 2012), the genetic relationship between BC and the neighbouring SK lobster populations remains uncertain (Truelove et al. 2015); regional genetic connectivity does occur between lobster populations from different MPAs within the MBRS (Truelove et al. 2014). Hence, the genetic connectivity of source and sink populations (Naro-Maciel et al. 2011), postlarval settlement levels (Briones-Fourzán et al. 2008, Butler et al. 2011), and the influence of ocean currents upon recruitment (Butler et al. 2008, Muhling et al. 2013), could shed a light on how to construct a local recruitment index, or help establish reference criteria to fit the estimates of recruitment levels for existing or future modelling assessments.

VI) a) The FISMO model (Ley-Cooper & Chávez 2009), has been updated since being published in 2009, and fishing mortality estimates (F) reported in (Ley-Cooper & Chávez 2009) were likely to be very specific, as several parameters were fixed at their true values, rather than arbitrarily estimated from auxiliary data (Harford et al. 2015). Unfortunately, much data required for the FISMO model was either insufficient or non-existent and had to be based on information from the existing literature (González-Cano et al. 2000a, Arce et al. 2001). Any actual mark-recovery procedure would have strongly benefited values produced by FISMO, as a reference for fitting the fishing mortality “F” to true exploitation estimates derived from field experiments (Goñi et al. 2010, Ley-Cooper et al. 2013),(Harford et al. 2015).

VII) An evident weakness of the FISMO model presented by Ley-Cooper and Chávez (2009), is the assumed relationship between spawning stock size and recruitment levels, as this is known as one of the most fundamental sources of natural variability in *P. argus* populations in the MBRS (Briones-Fourzán et al. 2008, Butler et al. 2008, Butler et al. 2011, Naro-Maciel et al. 2011). Although some lobster fisheries such as the Western Australian *P. cygnus* use both spawning stock and recruitment relationships for determining management strategies (de Lestang et al. 2012), establishing this relationship is not easily accomplished for *P. argus*, even where there is ample data (Cruz et al. 2001, Puga et al. 2005). As a stock recruitment relationship is assumed as a necessary precursor for the FISMO model, applying new and updated auxiliary data would improve accuracy by modifying the fixed parameters, thus drastically altering resulting scenarios (Ley-Cooper & Chávez 2009).

VIII) In Ley-Cooper and Chávez (2009), the scenarios depicted by simulations were purposely chosen by semi-arbitrarily assuming very low recruitment levels. Results were thus discriminated to select those where recruitment numbers were conditioned to be merely sufficient for restocking the exploited biomass, so the one year old cohort was the reference to adjust the estimated catch to the real catch values. The implication of this was that the number of lobsters recruited to the fishery, and consequently the estimated total population biomass volumes may have been underestimated. The decision to purposely assume low recruitment levels was taken knowing that self-recruitment is uncertain and puerulus settlement is most probably dependent on downstream southern populations which are being heavily exploited (Ehrhardt et al. 2010b, Truelove et al. 2014). As long term pueruli settlement studies to create indexes are unavailable in BC (Briones-Fourzán et al. 2008), source and sink populations remain unknown for Mexico (Naro-Maciel et al. 2011).

Likewise, variability in recruitment of multiple life stages, including the early juveniles among the BC population have not yet been sufficiently monitored to eliminate uncertainty in recruitment that causes caveats when assessing *P. argus* lobster populations in BC or anywhere in the MBRS (Cruz et al. 2001, Puga et al. 2005).

IX) If it is true that exploitation levels have been sustained without increased changes in effort occurring (Alvarez-Flores & Sosa-Cordero 2010), then it is likely that the MSY and MEY determined in (Ley-Cooper & Chávez 2009) overestimated the exploitation rates. Yet the fine balance between exploitation rates, recruitment levels and biomass estimates exist, and numbers could have resulted from multiple scenarios combining these variables. Certainly numbers should be revised before re-running the FISMO or any other assessment model in an updated version. Future attention must focus on monitoring the potentially diminishing biomass, increasingly low pueruli/juvenile recruitment levels, and indications of a reduction in catch rates (CPUE), as well as changes in size structure of the lobsters fished.

X) Poorly estimated catchability coefficients may result in inaccurate estimates of absolute stock size or fishing mortality (Smith and Addison 2003). Tagging experiments are recommended for fitting the stock assessment models and estimated outputs based on data from fishing effort, fishing mortality and movements (Harford et al. 2015). In turn these factors are affected periodically by ontogenetic, homing, or migrating behaviour, (Bertelsen 2013, Ley-Cooper et al. 2013) and may vary seasonally due to environmental factors such as autumn winds, storms and hurricanes, so will most probably affect the timely related mortality estimates in BC which should be monitored for this purpose (García et al. 1991, Caputi et al. 2013, Puga et al. 2013) (see further review in Chapter 7).

XI) Since there are indications of size differential distributions between shallow (< 20 m) and deep unfished habitats (>20 m) in BC (Ley-Cooper 2006, Ley-Cooper et al. 2014), catchability is likely to differ depending on size/age characteristics of the lobsters which are to be assessed (i.e. juveniles vs adults), and should be considered in future studies. Coupled with local ecologic factors, abundance may also depend on habitat and refuge availability, as these affect the different Stages of the ontogenic life cycle (Briones-Fourzán & Lozano-Álvarez 2013); so using auxiliary fishery data and habitat criteria, as well as incorporating distinct ecologic and lobster behavioural features into assessment models would highly increase the complexity and would highly influence the outcomes of predictive management scenarios (Harford et al. 2015), but would be recommendable for BC.

XII) Many changes have occurred in the BC fishery since the last stock assessment was carried out in 2010 (Alvarez-Flores & Sosa-Cordero 2010), and these would now need to be considered in 2015. Catch and effort values are likely to have changed, as the BC fishery has completely converted from selling lobster tails and using hook/gaffs for fishing, to catching live lobsters with snare loops and only selling them alive. It is quite likely that the technical capacity of catching live lobsters with snare loops reduces fishing efficiency, as searching time also increases, and therefore probably changes the effort factors of the average fishing time and catchability. These changes in fishing methods have increased catch landing volumes in up to three times with respect to 2008 simply because heads are not discarded, since the heads account for $\approx 60\%$ of the proportional total weight depending on the relative size of the lobster.

1.6.6 Constructing management measures in BC and SK through research modelling methods and biological criteria

Uncertainty associated with management of exploited stocks imposes the need to carry out qualitative risk assessments to prioritize issues for fishery management (Fletcher 2005). This requires applying precautionary measures to unknown variables in order to avoid possible stock depletion resulting in collapsed fisheries. Harvesting strategies need to be permanently assessed at different levels (Ríos-Lara et al. 2012), aiming to advise fishing cooperatives and decision-making agencies such as Fisheries and MPA's, that co-manage the exploitation of *P. argus* stock(s) at BC and SK..

Dynamic biomass models may provide estimates of a number of reference points in order to maximize economic benefits in lobster fisheries (Gardner et al. 2013), for example values for maximum sustainable yield (MSY); required fishing mortality for MSY (FMSY), fishing effort at MSY, biomass at MSY, as well as the biomass of the unexploited stock. These may be useful in assessing the condition of stocks and for framing management rules, but are obviously sensitive to model preferences (Ley-Cooper 2009, Alvarez-Flores & Sosa-Cordero 2010, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Harford et al. 2015). Punt and Hillborn (1996) warn of caution in shaping the relationship between catch rate and biomass, as mistaken estimates of catchability coefficients may result in inaccurate estimates of absolute stock size or fishing mortality.

BC and SK fishery conditions have changed since previous assessments as new data have been produced (Sosa-Cordero 2014) and assessment methods for determining fishing

mortality and exploitation rates have shown that it is preferable to include empirical data such as that from mark and recapture experiments (Ley-Cooper et al. 2013). There is also a need to incorporate the stock relationship between the deep unfished (>20 m) areas and shallows areas subject to fishing into fishery assessment models (Ley-Cooper et al. 2014, Harford et al. 2015). For example, the feasibility of reducing fishing mortality in BC by 0.025/ yr. as previously suggested by (Ley-Cooper & Chávez 2009), is not currently applicable in 2015. In addition to theoretical assumptions and parameters used in FISMO, the MSY estimated for BC in (Ley-Cooper & Chávez 2009) was determined with the premise of recovering stock biomass to historical catch levels previously obtained in the 1980's, when catches surpassed 60t (TW), which exceeds double the current volumes of $\approx 25t$ (TW). This seems unlikely in 2015, considering the low recruitment levels of pueruli sourced from depleted fisheries identified elsewhere in the MBRS (Chávez & Ley-Cooper 2007, Ehrhardt et al. 2010a, Truelove et al. 2015).

For BC, target threshold reference points have up until now been estimated with the principle of obtaining near optimal yields, while ensuring against stock collapse, and fishing below the estimated MSY level (Ley-Cooper & Chávez 2009). Although this was no doubt the correct approach, it is thus apparent that certain biological factors which were estimated for the BC fishery (such as growth, F and M), were questionable, indicating the need for more refined data, and fishery independent studies for comparison (Harford et al. 2015).

Fishery independent surveys must be carried out to monitor variable factors which will strongly affect stock biomass estimates (de Lestang et al. 2009, Penn et al. 2015), which are highly uncertain in parent recruitment relationship models for *P. argus* (Puga et al. 2005). Driven by many biophysical and genetic factors, uncertainty exists regarding pueruli settlement levels and population structure in the MBRS, as larvae are sourced from diverse and unknown locations, and further knowledge is required regarding recruitment processes into the local populations at early life stages (Briones-Fourzán et al. 2008, Butler et al. 2011, Truelove et al. 2014, Truelove et al. 2015). Additional research would empower fishery predictive models based on recruitment reference indexes, as has been achieved in Cuba (Puga et al. 2005) and Western Australia with *P. cygnus* (de Lestang et al. 2009).

Direct estimates of fishing mortality rates using mark-recovery techniques can help to shift policy focus away from difficulties inherent to accurate abundance estimation (Martell & Walters 2002). Actual tagging-based assessments can be carried out with alternative

marking processes with greater accuracy for indicating mortality rates as well as movement patterns (Frusher & Hoenig 2003, Ziegler et al. 2003 , Harford et al. 2015). These approaches would reveal movement patterns, clarifying the value of more detailed movement hypotheses, while also providing mortality estimates (Bevacqua et al. 2010).

Studies of the effects of alternative levels of effort in the near future (Puga et al. 2013), would enable relating fishery projections to local population parameters such as mortality and growth factors obtained from current biometric data sets. Environmental factors such as decreasing habitat availability and increased hurricane frequency should likewise be incorporated into the modelling equations and future risk assessments (Bellchambers et al. 2014). Construction of future simulations and models related to more data rich and informed scenarios, would then guide research priorities, in turn supporting development and implementation of input and output-based management systems, as occurs in other lobster fisheries around the world (Phillips et al. 2013, Penn et al. 2015).

Any future management strategy implemented in BC or SK should ideally be carefully re-assessed on a yearly basis, in order to evaluate whether the stock(s) respond according to predicted outcomes (de Lestang et al. 2012, Penn et al. 2015). Climatic variables (Caputi et al. 2013) and anthropogenic factors have been shown to be useful and necessary for assessing lobster populations,, as these have affected other *P. argus* fisheries like Cuba (Puga et al. 2013). The lobster stock(s) response to any effort reduction strategy should be monitored closely, as impact from changing climate and environmental effects may be causing mixed effects in the equations (de Lestang et al. 2009, Caputi et al. 2013). These aspects will be further reviewed in Chapter 7.

If the fishery was to continue following the MSC principles and criteria (Marine Stewardship Council 2010), one of the aims for managing this fishery will probably be pointed at regulating fishing mortality and establishing a set of harvest control rules (HCR's) (MRAG-Americas 2013), which would hypothetically be achieved through yield restrictions that will limit excessive fishing mortality. However, establishing yield limits requires knowledge of abundance or biomass, which can be difficult to quantify and estimate reliably (Haddon 2001, Hilborn 2002). Mark-recovery experiments may provide stock-wide fishing mortality estimates without first requiring abundance estimation (Lozano-Álvarez 1992, Harford et al. 2015), and community engagement in scientific research through a tagging program would be recommended for fishery assessments (Ley-Cooper et al. 2013), and useful

for establishing biological reference points, management measures and harvest control rules (HCR's).

Yield-based controls employed in conjunction with no-take areas have also been proposed as strategy for fishery management (Little et al. 2011, Penn et al. 2015). This is probably the direction for future management in BC and SK, entailing officially assigning the deep >20m area as a no take zone for lobsters, to be further discussed in Chapter 9.

The casita/campo implementation plan that is to be detailed in Chapter 4 is expected to change the fishery dynamics and exploitation in BC. Alterations in habitat use by lobsters are expected, fishing mortality and juvenile survival levels might drastically change over time and these processes should be closely monitored (Lozano-Álvarez 1995, Briones-Fourzán & Lozano-Álvarez 2013, Gutzler et al. 2015) in order to better understand the local population dynamics, and continue to manage both BC and SK fisheries sustainably.

1.7 Chakay and MSC: Eco-labelling initiatives within the Sian Ka'an and Banco Chinchorro Biosphere Reserves Mexico.

Short note: Some figures and fragments of this section refer to the article published in Proceedings of GCFI, 63 (Ley-Cooper 2010).

In the previous sections of this literature review we have overviewed several aspects of the BC and SK *P. argus* fisheries, but we have focused on biological aspects considering fishery science methodologies and criteria including the analysis of population genetics, and stock assessment modelling. In this section we will overview the fisheries SK and BC from a wider perspective, focusing more on the social, governance and economic effects on which the CHAKAY (IMPI 2009) and the MSC (MSC 2014) ecolabels have impacted.

An general perception of both ecolabelling schemes which are currently used and registered by the six cooperatives that fish in the SK and BC MPA's (IMPI 2009, MRAG-Americas 2013), is that they have been an innovative way to gather all stakeholders around the need to assess the status of these fisheries, study certain aspects of the *P. argus* populations and search for ways of increasing compliance with management arrangements (Ley-Cooper 2010, Velez 2014). The expectations are that these initiatives may lead to more sustainable fisheries if recommendations for management measures derived from the annual evaluation processes are to be followed (MRAG-Americas 2013), (Ward & Phillips 2010, Pérez-Ramírez et al. 2012b, Ward & Phillips 2013), but more importantly the idea of the Chakay and MSC ecolabelling schemes are supposed to be useful for generating a value

addition to lobsters, if the market capitalizes on good practices as a sales strategy. Here I review the general outcomes and effects of the commercial aspects promoted by the implementation of ecolabels. I also refer to the legal strategy that intends to increase compliance, while discussing how these ecolabels may be used as instruments to assist in encouraging continuous scientific research, monitoring and assessment of the *P. argus* stocks and their environment.

1.7.1 Building a National eco-labelling scheme for Sustainable lobster- “Chakay”

Sustainability is a rapidly and increasingly applied area of study, which is often hard to define especially in the context of fisheries (Pauly et al. 2002a, Jacquet et al. 2010, Ward & Phillips 2013, Bellchambers et al. 2014, Pérez-Ramírez et al. 2015). The definition put forth in 1983 by the World Commission on Environment and Development was: “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*” The manner that sustainability is manifested often varies with the field of study. The principles and criteria for evaluating sustainability of fisheries from a multidisciplinary perspective, to include ecological, environmental, social and economic aspects turns out to be a very complex process (Caddy & Seijo 2005, Seijo 2007, Pérez-Ramírez et al. 2015), but a necessary task in the SK and BC fisheries; as these have been certified by MSC as being sustainable yet the direct benefits are still not evident for most stakeholders.

The word “Chakay” meaning lobster in the Mayan language is the trademark name which has been registered as an eco-label by the fishing cooperatives that fish in the BC and SK Biosphere Reserves (IMPI 2009, Ley-Cooper 2009, Ward & Phillips 2010). As with other ecolabelling schemes (Ward & Phillips 2013, Pérez-Ramírez et al. 2015), Chakay was conceived as a means to add value and achieve sustainability of the SK and BC *P. argus* fishery without having to increase the fishing effort, while still satisfying commercial demand and engaging all stakeholders and government agencies in charge of management of these fisheries (Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011). The initiative is centred on promoting better management strategies and applying principles and criteria for sustainability to *P. argus* lobster fisheries within the context of the SK and BC Biosphere Reserves (Ley-Cooper 2010, Ward & Phillips 2010), with reference to existing information regarding the local populations and published scientific knowledge on the species (Arceo et al. 1997, Puga et al. 2005, Briones-Fourzán et al. 2007), (Cruz 2002, Sosa-Cordero et al. 2008, Alvarez-Flores & Sosa-Cordero 2010, MRAG-Americas 2013, Ley-

Cooper et al. 2014, Origlio et al. 2014). The design of the scheme is intended for updating the trademark's rules of use every so often, in order to achieve a changing management system that adapts to the current needs for achieving sustainability.

Chakay is officially the first national marine collective trade mark to have been registered and accepted as an eco-label in the Mexican Institute of Industrial Property (*Instituto Mexicano de la Propiedad Industrial*)(IMPI 2009). The ecolabelling scheme consists of having a commercial logo with a specific design and name “*Langosta Chakay*”, followed by the words: “*from the Banco Chinchorro and Sian Ka'an Biosphere Reserves*”, which provides the indication of protected origin (provenance). This logo is in turn linked and defined by the “rules of use” that govern its commercial use and also penalizes its misuse internally within the cooperatives, and externally as with any other trade mark. The rules of use are the legal tool associated with the eco-label which may be used to enforce governance by applying the Mexican national and international normativity related to marketing of any commercial label that has been registered (IMPI 2009). In addition to the MPA's and the fisheries existing legal framework (Ríos-Lara et al. 2012), the eco-label therefore represents an additional way of improving management and regulation of the fishery, by converging other Mexican norms and regulations, which were not previously directly related to these fisheries.

Sustaining the local *P. argus* lobster population(s) and preserving the socioeconomic condition of fishers are two of the main goals implicit in the rules of use for the Chakay eco-label (Ley-Cooper 2010, Ley-Cooper & Quintanar-Guadarrama 2010). Government institutions and NGO's promoted this scheme to the fishing cooperatives with the aim of adding value to the product while applying principles and criteria of sustainability, as expressed in the rules of use that govern the eco-label (IMPI 2009).

The “Integradora de Pescadores de Q. Roo” (IPQRoo) was registered as the commercial entity (owner) of the Chakay eco-label, which represents all six cooperatives, which own exclusive rights for fishing within the two protected areas of SK and BC (

Table 1-3). This socio-economic arrangement is known as a second floor enterprise, providing an innovative way for commercialising the sustainably fished cooperative products under one unique commercial structure: the Administrative Council (Ley-Cooper 2010, Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011). Whilst forming part of the “Chakay” eco-label initiative, the General Assembly is in turn represented by the

Administrative Council, composed essentially of members/presidents of the six cooperative's, which decide upon the Integradora enterprise.

The administrative structure of the IPQRoo allows for a guided governmental and stakeholder intervention through the Steering Committee (consejo consultivo), which in turn is integrated by Governmental authorities, academic research centres and Universities, NGO's, as well as representatives from industry. In collaboration with the fishing cooperatives, the Steering Committee is required to periodically assess and update the Chakay eco-label Rules of Use, as well as evaluating the administrative operations of the associated cooperatives. The IPQRoo scheme is intended to leverage all six cooperatives simultaneously at a higher level, in order to increase compliance with sustainability policies and management arrangements, designed to improve fishery practices. Rules of use are supported through product regulation of lobsters fished and sold by IPQRoo, or any of the associated cooperatives under the eco-labelling scheme, as well as providing support, vigilance and monitoring of the fishery in the field; this is also enhanced by market driven interests.

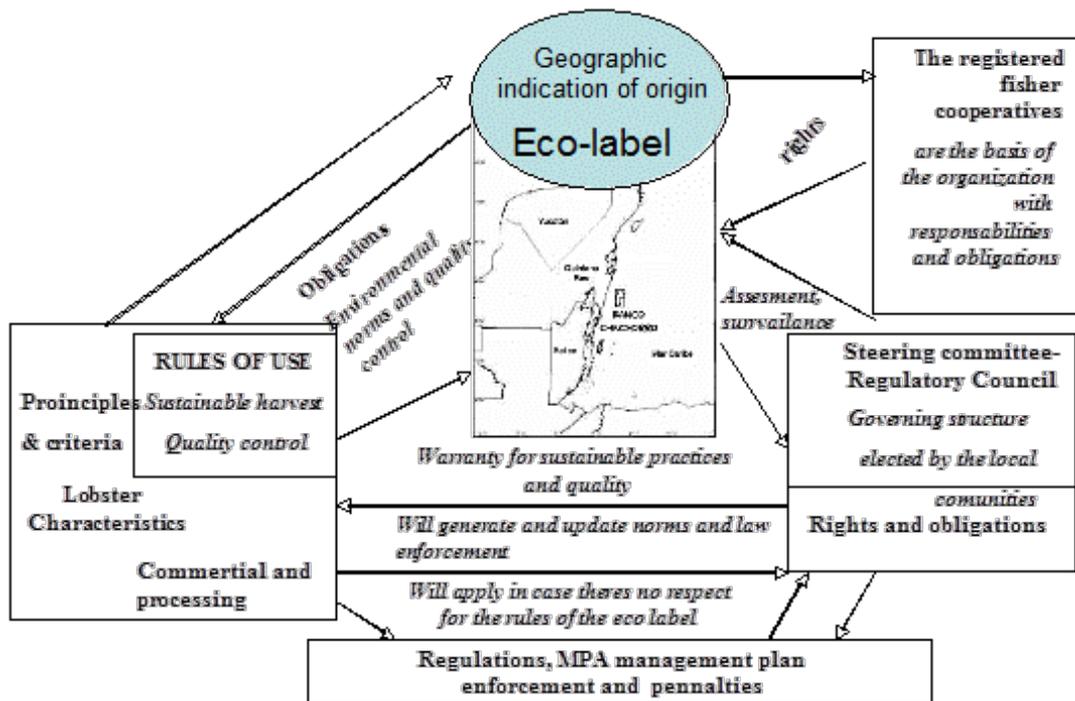


Figure 1-21: Governance scheme of the Chakay eco-label of the *P. argus* lobster fisheries in the BC and SK Biosphere Reserves, Mexico.

Implementation and application of the “Chakay” eco-labelling scheme that is partially sponsored by government agencies, is contemplated as a way of meeting commercial demand

and achieving sustainability among lobster populations in SK & BC as this adds value to the product, and acknowledges the historically sustainable fishing practices of these cooperatives, which have managed to maintain a constant catch throughout the last two decades with their artisanal fishing practices (Sosa-Cordero et al. 2008, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013). These are some of the main reasons why these two fisheries have been certified as sustainable by the MSC (see section 9.3 for details) (MRAG-Americas 2012). The “Chakay” eco-label is also intended to function as a tool for permanently promoting change in fishing technology and gear, as this encourages adaptation to fishery management strategies complying with future needs in both these MPA’s.

The Chakay initiative, has led several multidisciplinary projects, such as the implementation of biological monitoring programs for evaluating the BC and SK lobster population(s); initiatives for changing fishing techniques from gaff to snare loops in BC (Ley-Cooper 2009); and the use of artificial shelters ‘casitas’, as a viable alternative for increasing BC juvenile recruitment to the fishery (see chapter 4)(Ley-Cooper et al. 2011),,(Briones-Fourzán & Lozano-Álvarez 2001a). This has led to the opportunity for changing fishing gear, providing equipment, and carrying out fishers training projects. A recent example of success was the fishers exchange program to incite modifications of capture techniques and the marketing of live lobsters instead of tails in BC (Ley-Cooper & Garcia-Rivas 2009). This strategy aimed to eliminate the hook/gaff method and increase landings without having to intensify fishing effort, simultaneously improving selectivity, reducing mortality of egg bearing females and undersized lobsters (i.e. <135 mm tail length, <75 mm CL) for management purposes, while gaining better price for quality and net weight, adding value, by using the Chakay eco-label as a commercial tool.

Previous initiatives for casita instalment in BC were designed for assessing movements, growth and prevalence of the PAV1 virus in lobsters (Ramírez-Estévez et al. 2010). Following the effects of Hurricane Dean in 2007, the more recent initiative for implementation of casitas (Ley-Cooper et al. 2011). The idea was originally intended to restore BC’s *P. argus* population, and slowly abandon the reefs, with the condition that the participating cooperatives would divide the MPA’s lagoon to create the necessary Campos, where casitas are to be placed under the similar arrangement as in Sian Ka’an (see sections 1.6.4.1.1 and chapter 4) (Sosa-Cordero et al. 2008, Briones-Fourzán & Lozano-Álvarez 2013).

Casita implementation is currently not complete as projected for 2011 (Ley-Cooper et al. 2011), as Hurricanes Dean and Ernesto in 2012 destroyed the wooden trial casitas that had been installed for evaluation. However, catching lobsters with loops and snares to sell them alive represented a very successful program, as today the cooperatives in BC are fully converted to using snares and have practically eliminated the hooks. In 2015 lobsters are now only sold whole/alive, with up to a 30% gain in price with respect to tails, increasing the average catch landings up to more than three times from 20 t tail weight in 2010, to >60 t in 2013 whole weight (CONAPESCA-SAGARPA 2013). This initiative has greatly been encouraged by the ecolabelling initiative, providing an excellent example of collaborative, multidisciplinary effort.

1.7.2 The MSC context:

While some fisheries around the world are being fished and managed sustainably, the increased profile of stock sustainability and the potential impacts of fishing practices on the environment has led to an increased awareness of environmental issues on the part of the general public and conservation groups (Bellchambers et al. 2014). There are a number of third party certification programs such as Global Environmental Facility – GEF, Friends of the Sea, Naturland, and others (Ward & Phillips 2010), yet one popular certification programme with worldwide coverage is the Marine Stewardship Council (MSC) (Marine Stewardship Council 2010).

Established by World Wildlife Fund (USAID-CAFTA-WWF) and Unilever in 1999, the MSC is now an independent international non-profit organisation that certifies ecologically sustainable fisheries to give them an economic incentive to implement and maintain sustainable fishing practices (Cummins 2004). Currently the MSC has certified 221 fisheries and a further 98 are undergoing the assessment process (MSC 2014). Since the first certification of the WA rock lobster fishery in 2000, several other lobster fisheries have been MSC-certified: Eastern Canada off shore lobster, Maine Lobster trap fishery and Iles-de-la-Madeleine lobster fishery (*Homarus americanus*), Normandy and Jersey lobster (*Homarus gammarus*), Tristan da Cunha rock lobster (*Jasus tristani*), Mexico Sian Ka'an and Banco Chinchorro Biosphere Reserves spiny lobster (*Panulirus argus*) and Mexico Baja California red rock lobster (*Panulirus interruptus*), Juan Fernandez lobster fishery (*Jasus frontalis*), whilst others are in the process of assessment (Bellchambers et al. 2014).

The MSC certification process involves independent third-party assessments of a fishery based on evaluations made considering three broad principles; P1 – assessment of target species, P2 – ecological and environmental impact of the fishery and P3 – governance and management of the fishery. For a fishery to successfully obtain MSC certification, it must individually fulfil each of three principles, i.e. scores cannot be averaged across principles (Marine Stewardship Council 2010). The result is that while fisheries targeting species with sustainability issues (P1) will clearly not obtain MSC certification, neither will fisheries making substantial ecological or environmental impact (P2) or manifesting inadequate governance and management, regardless of the status of the target species stocks. For many fisheries, MSC certification has meant additional scrutiny and review of existing processes (Bellchambers et al. 2014), and this is the case in SK and BC (MRAG-Americas 2013). With dubious consumer acceptance in Mexico (Pérez-Ramírez et al. 2015), a reaction similar to that of some fishers in Baja California's *P.interruptus* fishery in the Pacific Coast of Mexico (Pérez-Ramírez et al. 2012b), MSC certification during 2015 has been perceived in BC and SK as a bureaucratic load which is expensive to maintain,. However it has also offered an important opportunity for multiple interests to converge, around the lobster fisheries sustainability.

2 CHAPTER 2: Introduction to the thesis

2.1 Concluding remarks derived from literature review

The *P. argus* fisheries in Banco Chinchorro (BC) and Sian Ka'an (SK) Biosphere Reserves have been certified as being sustainable by the MSC in 2012, as they have successfully passed the assessment carried out against the criteria established in the principle documents (Marine Stewardship Council 2010, MRAG-Americas 2012, MSC 2014). This certification will probably continue, , provided the conditions established are addressed as a series of goals regarding management arrangements, gathering and evaluating fishery stock information, along with the assessment of the impact of this activity on the environment (Marine Stewardship Council 2010, MRAG-Americas 2012, 2013, Bellchambers et al. 2014). Throughout this study many of these and other issues regarding the sustainability of these fisheries are addressed from a scientific and socio-economic perspective.

The fisheries in the BC and SK MPA's are evaluated from various points of view and technical capacities, ranging from micro (genetics) to macro (population) scales using a wide range of innovative techniques of analysis, to assessing socioeconomic aspects from a socio-anthropologic dimension. Work extends from desktop reviews of the most current pertinent literature regarding sustainability aspects (Agnew et al. 2013, Phillips 2013, Bellchambers et al. 2014, MSC 2014, Velez 2014 , Pérez-Ramírez et al. 2015); to the analysis of fishery dependent data (i.e. biometrics, catch and effort) (Donohue et al. 2010, de Lestang et al. 2012, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014); assessment of population genetics aspects in the laboratory (Truelove et al. 2014, Truelove et al. 2015); to implementing mark and recapture experiments in the field (Bertelsen 2013, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

As a result, stock assessment models are produced and new knowledge is shed regarding the local BC and SK *P. argus* populations in Chapters 5, 6, and 7. After a thorough review in the core chapters, evaluation of sustainability aspects of the SK and BC fisheries is carried out in the remaining chapters, but a review of the broader picture occurs in the Discussion Chapter 9, Section 9.1. For example connectivity aspects of the local and regional *P. argus* populations are carried out in Section 9.2, and a detailed evaluation of sustainability performance indicators is developed in section 9.3. The thesis includes a revision of the effects on future management 9.3.3 arrangements and possible scenarios, as well as proposals

for future research, which are discussed throughout the thesis yet mainly concentrated in the discussion section of Chapter 9.

Trends on catch data for BC and SK have shown a relatively stable catch during the past two decades (Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007, Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013); where total tail catches have varied around 20 t-TW (65t-WW) for the three cooperatives in BC; 100t (WW) for BA SK (Punta Allen) Vigia Chico; and 30 t (WW) total capture for BES SK Southern Bay both Cozumel and Azcorra cooperatives, respectively (Ríos-Lara et al. 2012, CONAPESCA-SAGARPA 2013). It would seem that these catches have been possible without any apparent increase in effort in recent years {(Ley-Cooper et al. 2013, (Ley-Cooper, 2014 #244)}(Ley-Cooper et al. 2014) which is contrary to patterns observed in other Caribbean fisheries (FAO 2001, de León et al. 2005), and has been the principle benchmark for government and stakeholders to embark on the journey towards eco-labelling initiatives for this fishery such as Chakay trademark and MSC certification (Ley-Cooper 2010, Ward & Phillips 2010, MRAG-Americas 2013). All these aspects motivated this thesis and are reviewed throughout the different Chapters.

As detailed in Chapter 1, the community-based fishers are organized into cooperatives that follow strict regulations related to their artisanal fishing practices. Skin diving, without alternative air source equipment, and the use of artificial dens/casitas in a system of individually owned marine plots are their only technology for capture (López & Consejo 1986, Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998). This limits the exploitation beyond the depths of 15-20 m. (Lozano-Álvarez et al. 1991b, Sosa-Cordero 2003, Ley-Cooper 2006, Ley-Cooper et al. 2014). Licences are renewed annually and cooperatives must comply with the current legislation that includes a closed season from March to July, a minimum capture size of 135 mm tail length, and avoidance of the capture of ovigerous females as well as with other internal management rules. Historically the semi-ownership of the fishing plots has allowed self-surveillance and has been thought of as an efficient management strategy for regulating the fishery, which operates in areas that are closed to public use (Lozano-Álvarez et al. 1989, Seijo & Fuentes 1989, Sosa-Cordero et al. 2008, Ley-Cooper et al. 2014). The effectiveness of these MPA's management, as well as the cooperative's social arrangements with regard to the *P. argus* fisheries are reviewed and discussed throughout the different Chapters of this thesis...

The SK and BC Marine Protected Areas have been declared as Biosphere Reserves for more than two decades (López & Consejo 1986 , INE-SEMARNAP 2000), and evidence suggests that environmental factors may have favoured the lobster's natural biological processes such as recruitment, reproduction, growth, and migration, all of which have thus helped to sustain the current stock sizes and captures (Lozano-Álvarez 1992, Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007). However, the specific biological features of the local *P. argus* populations must be regularly and systematically monitored, revised, and analysed in a scientific manner in order to assess sustainability (Wright et al. 2006, Bellchamers 2009). Consideration of the species biology and the effects on the fisheries characteristics (Thomson & Caputi 2005, Penn et al. 2015), along with assessments in this regard are carried out to a great level of detail in Chapters 4,0,6 and 7.

Seijo and Caddy (2000) point out that: “The development of management plans for marine living resources requires systematic integration of aspects of the resource biology and ecology with the economic and social factors that determine fishers' behaviour over time”. There is ongoing debate on whether *P. argus* populations throughout the Caribbean are interconnected and should be conceived and evaluated as a series of “meta-populations” or many small independent stocks, (González-Cano et al. 2001, Ehrhardt et al. 2010b, Truelove 2014, Truelove et al. 2015) mainly due to larval dispersion and the complex life cycle history (Briones-Fourzán et al. 2008, Butler et al. 2008, Naro-Maciel et al. 2011). As reviewed in section 1.5, resolving this question would require an extensive, long term genetic study and is beyond the objectives of this thesis work, although some very important population genetic results have been published (Truelove 2014, Truelove et al. 2014) and will be further discussed in Chapter 0.

Implications of the latter biological/connectivity aspects of the *P. argus* species, with regard to the existing management units and boundaries are thoroughly discussed in section 9.3.1.1.1. Yet for the purpose of this thesis, the BC and SK will be referred to and evaluated as independent *P. argus* stock units, when assessing biological characteristics, population dynamics and fishery related aspects, as previously discussed in sections 1.6.3 and 0. Hence the SK Biosphere Reserve will be subdivided into the Northern Bay-Bahía de la Ascensión (BA) (Figure 1-7), and the Southern Bay-Bahía del Espíritu Santo (BES) (Figure 1-8 and Figure 1-9) considering the corresponding cooperatives in each area (Table 1-4). However, when commercial aspects are mentioned, these may be referred to as a single unit, as referred

to in the Chakay and MSC eco-labelling schemes (Chafee 2008, Ley-Cooper 2010, MRAG-Americas 2013).

Although previous publications have assessed these fisheries and have suggested that fishing mortality and effort should not increase in BC nor SK (González-Cano et al. 2000a, González-Cano et al. 2000b, Sosa-Cordero 2003, Ley-Cooper 2006), Ríos-Lara 2012, (Ley-Cooper et al. 2013), further research on population dynamics and fishery characteristics, is still required to evaluate the current status of the fisheries, assess effort, catch rates, and exploitation rates, from a current perspective (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), including spatial assessments (Ley-Cooper et al. 2014); as is proposed and developed in chapters 5,6, and 7.

Throughout this thesis sustainability aspects will assess the dynamics of the local *P. argus* populations, the biological characteristics of the stocks (Chapter 5 and 6), environmental aspects related to the fishery (Chapter 7), and genetic connectivity (section 9.2) these are the core scientific segments which are based on empirical data analysis. However economic and social dimensions of these fisheries at BC and SK Biosphere reserves are also evaluated (Chapters 4, 8 and 9), as well as changes which have occurred regarding fishing methods and fishing gears in BC (Chapter 4) (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009). Within the context of the MSC and Chakay eco-labelling schemes, we examine the casita implementation initiative (Chapter 4) and other management measures in terms of the impact on sustainability aspects of these fisheries (Chapter 9). We include analysis of the potential economic and marketing benefits of certain management measures (Chapter 8), and evaluate their effects on the fisheries and local *P. argus* populations (Chapter 9). The last section is based on results from this thesis and suggests future research for further assessing sustainability aspects of these fisheries, within the framework of existing management schemes and needs (Ríos-Lara et al. 2012, MRAG-Americas 2013).

2.2 Aim

To evaluate the sustainability of the *Panulirus argus* fisheries at Sian Ka'an (SK) and Banco Chinchorro (BC) Biosphere Reserves in southern Mexico.

2.3 Objectives:

To achieve the main objective of this thesis which is: **“To assess sustainability of Lobster *Panulirus argus* Fisheries in Marine Protected Areas in South-eastern Mexico”**,

the following **general objectives** were designed to set the baseline information which was further assessed and developed in each Chapter:

1. To record the catch and effort (#boats, #fishers, daily catch rates), and biometric characteristics of the *P. argus* lobsters such as size, weight, sex, state of sexual maturity, and relate these to population parameters such as growth, distribution, movement patterns and exploitation rates at SK and BC.
2. To develop and conduct independent surveys at different depths, in order to estimate the proportion of the *P. argus* population that is not subject to the fishery (>20 m), by using mark-recapture techniques, at BC and SK.
3. To re-evaluate the existing, and to recommend new techniques for analysis and management of the lobsters populations at SK and BC.
4. To research and determine biological reference points for stock assessments at SK and BC
5. To investigate the eco-labelling initiatives and principles for sustainable commercialisation, and their effects on the socio-economics of the fishery.
6. To conduct socio-economic analysis of the changes resulting from the implementation of the eco-labelling schemes which are currently taking place, as a means of investigating their effects on the sustainability of the fishery.
7. To produce a series of recommendations for long term monitoring, assessment and management of these fisheries.

These general objectives mentioned above gave rise to a series of specific objectives and activities that were further developed in the individual chapters. For example in Chapters 5 and 6, specific objectives were established for evaluating tag and recapture data to estimate fishing and natural mortality, as well as for carrying out experiments to estimate tag loss, and to develop the corresponding modelling methods. In Chapter 7 there were specific objectives related re-interpreting fishery data to develop Catch Rate Indexes that would allow us to assess environmental effects derived from cold fronts. The list of specific objectives elaborated for each chapter are detailed within the context and not repeated here for practical reasons. However in the next Significance (section 2.3.1), I have explained how the main contributions of this thesis tackled the research objectives mentioned above.

2.4 Significance

It is expected that the knowledge obtained during this study will provide a better understanding of the long term sustainability needs of the *P. argus* lobster fisheries in the Caribbean, and help improve the livelihoods of the artisanal fishers by providing a series of recommendations for improving management and achieving sustainability. This research will provide an opportunity to gather and evaluate information for assessing the *P. argus* stock(s) and local population dynamics at the SK and BC Biosphere Reserves. It will produce a series of recommendations for improving monitoring and research techniques, evaluate and discuss alternative management policies and measures, evaluate fishing practices, and suggest commercial tools for adding value to maximize socioeconomic benefits across the commercial chain, without increasing fishing effort. It is expected that recommended measures for improving management may increase local governance, provide technical tools for assessment, and shape ideas for improving sustainability in the MBRS within a community based framework.

2.4.1 Main contributions of this thesis

For objective 1:

- i) Continuous and systematic measuring of the biometric parameters on boats for periods of 2, 3 and 4 years in BC, SK-BA, and SK-BES was carried out in order to update biological criteria and assess current population parameters.
- ii) Catch rates and associated catch per unit of effort were determined by assessing number of fishers, number of trips, number of casitas fished, number of campos fished as well as coding for specific locations according to knowledge of “common” names used by fishers. This occurred from both current and historical data sets covering daily and yearly information which required structuring, cleansing and filtering data for a more precise evaluation.
- iii) Tagging data was produced for evaluating local movements’ migration patterns and exploitation rates.

For Objectives 2, 3 & 4

These were mostly developed in chapters 5, 6 and 7 (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014) by:

iv) I designed a tag-recapture program including laboratory tests for tag loss and survival of *P. argus* was undertaken in BES and BC during the closed seasons of 2009 and 2010, whilst recovering data up to 2014.

v) For stock assessment purposes, I acknowledged that previous models used in the area (simulation and depletion) which allowed for estimation of fishing mortality, were constrained in regard to their capacity to incorporate tagging data. As a result I opted for further developing the Brownie model (Brownie et al. 1978) in a more refined modelling framework that allows for producing estimates of fishing mortality, exploitation rates and biomass of lobsters in these areas using the tag recapture data and information.

vi) The Brownie model developed was also used to assess uncertainty of these estimates and their sensitivity to alternative assumptions regarding the life history, movements, migration pulses and distribution patterns of lobsters in these populations.

vii) One of the main contributions of the modelling approach (Ley-Cooper et al. 2014) included the evaluation and implications of having an unfished area in the deep (>20 m) portion of the stock. This allowed for an analysis of the interdependencies between the near-shore exploited portion of the stock mainly composed of juveniles and young adults and the deeper, unexploited portion of the spawning stock.

For research Objectives 5 & 6

viii) Analysis of socioeconomic factors related to the new CHAKAY and MSC eco-labelling schemes were carried out by semi structured surveys before and after the certification occurred in 2012 (details regarding methods are further discussed in Chapter 8). Variables considered included expenditures, incomes, and possible changes of revenue from added value linked to the new capture methods implemented. This research effort contributes to the assessment of eco-labelling benefits and costs.

For Research Objective 7

ix) A participatory approach was undertaken to identify personal and group based fisher community recommendations for long term monitoring assessment, and possible commercial strategies that could foster sustainability for the BC, and SK fisheries. Since sustainable governance of these fisheries requires participation and commitment of stakeholders with alternative management strategies currently under consideration, this thesis contributes to this approach of sustainability.

x) Finally the discussion Chapter 9 is structured so that it follows a practical format based on the three main MSC principles (Stock Assessment-P1, Environmental impact of

the fishery- P2, and Fishery management arrangements-P3); which enabled me to deliberate around sustainability aspects of these fisheries, considering different criteria, based on the information and data gathered, documented and produced throughout the development of this thesis project, including self and co-authored published articles and materials. In acknowledgement of the fact that BC and SK may be perceived as independent or interdependent units of certification, based on the scale and method of the assessment in place, the thesis includes a comprehensive overview and analysis of connectivity aspects of the local and regional *P.argus* Metapopulation, a detailed evaluation of sustainability performance indicators, a revision of future management arrangements and possible scenarios, as well as suggestions for future research to tackle questions still unanswered by this thesis.

xi) In addition to the scientific insights presented, I have integrated my research activities with resource users and managers, and collaborated effectively with a wide group of individuals across disparate international boundaries. I have stretched the boundaries of my knowledge to integrate into this thesis pure marine science, meteorology, socio-economics, fisheries science and management.

3 CHAPTER 3: General Materials and Methods

This chapter describes general materials and methods that were used to gather information evaluate and assess the SK and BC fisheries in the light of sustainability. However the methodologies used are further detailed and described in each individual chapter according to the specific hypothesis which were stated for each section.

The fieldwork activities, desk work collection and processing of historical data, as well as current fishery independent data were carried out in a participative manner in many cases. This was possible due to existing inter-institutional collaborations, which included a consultation process and interviews with many members of the six fisher cooperatives that own exclusive rights for fishing in BC and SK. All research was carried out with the given permits required for research activities within the MPA's.

3.1 To achieve objective 1

A group of over eight people have participated throughout the duration of the project at different stages and sometimes simultaneously, in order to ensure continuity and quality controlled data of the biometric parameters such as weight, sex, length, and sexual maturity (Lozano-Álvarez et al. 1991b, Lozano-Álvarez 1992, Bellchambers et al. 2009, Bellchamers 2009). Two biologist as technicians, one in BC and one in SK had six fishers assigned by the cooperatives to help in boat operations and tagging activities three for BC and three for SK. All staff was trained, coordinated and constantly supervised by myself and or other experienced researchers for systematically measuring the biometric parameters of caught lobsters, and gathering useful data to determine catch rates/CPUE (# fishers, # immersions, time spent underwater, # of casitas or sites visited during the day) and total effort including partial and total boat and cooperative capture per day, month and year. Work involved surveys and logbooks data gathering of at least 30% of the total catches landed per boat trip for the fishing seasons in 2009, 2010, and 2011 which were assessed in BES-SK and BC.



Photo 3-1 Collecting Biometric, biological and relevant data in BC; Length frequencies (CL), sex (M,F), reproductive condition (presence of tar spot, eggs), number of missing legs and antennae, recording presence of PaV1 virus disease, and GPS position were recorded for each *P. argus* lobster caught in natural refuges (mainly reefs) and casitas.

Surveys derived from logbook biological information were always confirmed and ratified with both a) daily captures registered for internal cooperative accounting and administration and b) information delivered by cooperative nursing boats at product reception sites used for governmental taxation and fisheries statistics. Before the each of the fishing seasons begun as from July 2009 to February 2013, a scouting meeting with CONANP staff and fishers was held in order to prepare and coordinate the fieldwork to be carried out during the season in BC and SK, and to ensure the generation of supervised good quality biological and fishery data in field. Fisheries practical procedures such as catch rates, catchability, and index of removal were calculated from this data, all of which are indirect methods of estimating population sizes, fishing mortality and exploitation rates (Melville-Smith & de Lestang 2006, Goñi et al. 2010, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Pollock et al. 1985).

3.2 To achieve objective 2, 3 & 4

Mark/Tagging and recapture program 2009-2011 for Bahía Del Espíritu Santo-SK and Banco Chinchorro:

For further details on the protocol (see chapters 0, 6 and 7). Lobsters were tagged in Bahía del Espíritu Santo SK and Banco Chinchorro during the months of April/May 2009 and 2010 which was the closed season. The area of the bay where casitas were distributed was divided into sampling zones and lobster tags were applied following the protocol described in each chapter. Only animals >44 mm CL were tagged in order to reduce incidental mortality. Tags were inserted into dorso-lateral extensor muscle between the cephalothorax and first abdominal segment. After tagging, lobsters were immediately released, at the same location where they were caught. Tag number, date, release location, sex, reproductive state and

carapace length (CL ± 0.1 mm) were measured between the rostral horns to the posterior dorsal edge of the carapace, and were recorded. When lobsters were sold as tails, fishers were requested to keep the head of recaptured lobsters together with the tag so that the CL could be measured and provide recapture date and location (Lozano-Álvarez et al. 1991b, Wright et al. 2006),(Goñi et al. 2010, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

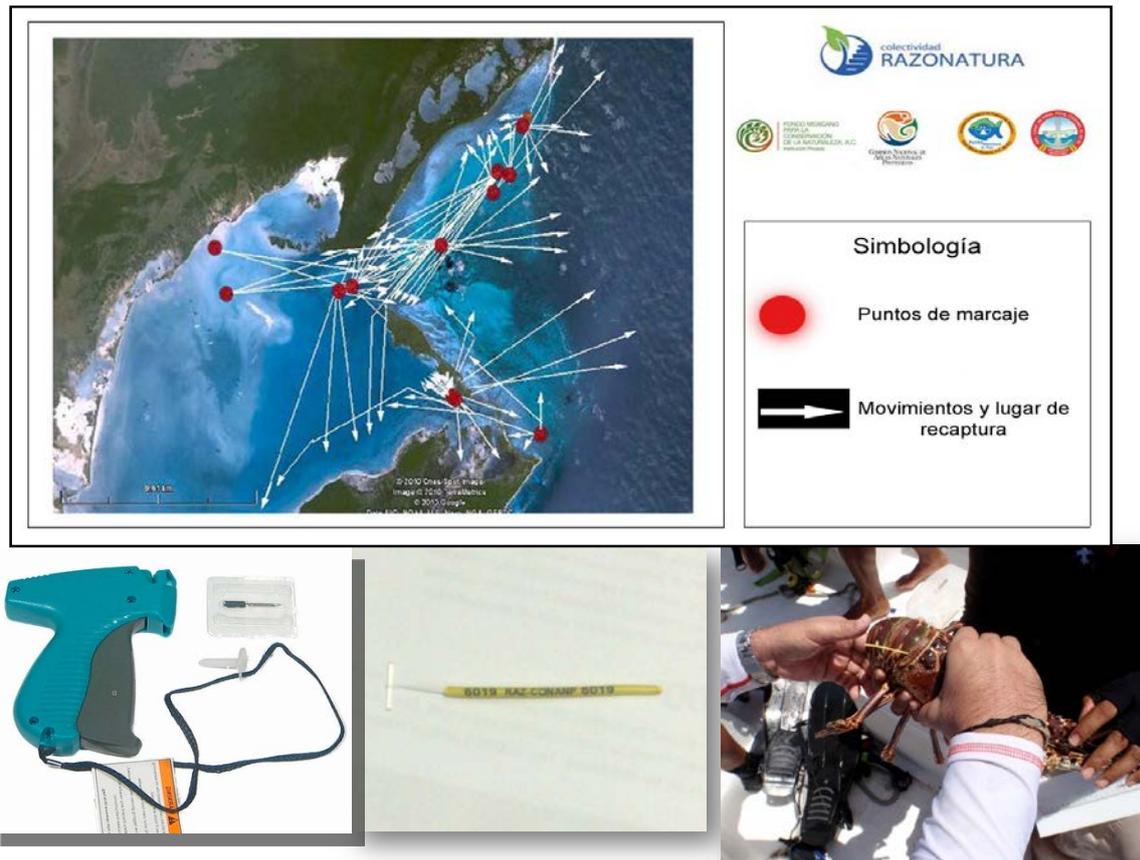


Figure 3-1 Top left shows the map of Bahía del Espíritu Santo in SK where lobsters were tagged at several sites (red dots), and the arrows showing direction and areas where some lobsters were recaptured during the 1st year of study. Bottom panels from left to right show a) the tagging gun b) T bar tags used and c) the tag placed on a *P. argus* lobster.

As both BC and SK fisheries are limited by depth, and skin divers can only fish the lobsters in shallow waters < 20 m, the twenty meter depth was used to determine the boundary between the deep unfished stock and the shallow stock subject to fishing, which were evaluated and assessed by an *ad hoc* model developed for this purpose (Ley-Cooper et al. 2014). A large number of lobsters were required for an effective tagging study, so two

different fishing methods were used a) SCUBA diving in the deep reefs and b) skin diving under shallow reefs and casitas, as fishers regularly do.

A tagging regime was conducted at different depths and locations (north, south, east and west) in BES SK and BC. The GPS position of each casita was recorded, as well as all biological information of each lobster, casita and campo that were fished and sampled during off season and during the fishing season. All lobsters caught in casitas had carapace and tail length measured to the nearest mm, and sex and reproductive state recorded. Lobsters were tagged with T-Bar tags Hallprints Ltd, using the methods outlined in each section and returned to the water at the point of capture.

3.2.1 Diving based surveys:

Diver based surveys were conducted in the deep sites (>20 m). At each site two teams of two divers conducted 50 m long x 2 m wide transects to survey the areas of potential refuge, catch and tag lobsters. All of the lobsters examined were measured, sexed, tagged and returned to the water at the initial point of capture. The combination of casita, reef and diver based surveys provided different yet complimentary techniques that allowed a more comprehensive examination of abundance and size distribution and ensured that a sufficient number of lobsters were captured across all size classes and in all areas. This research also allowed an assessment of movements and migration patterns, including distance and timing, by the recapture of tagged lobsters throughout the year (see chapters 0, 6 and 7). The tagging programs were advertised widely and a reward program was introduced to encourage tag returns.

3.2.2 Tag loss

For details (see chapters 0, 6 and 7) at UNAM university lobsters were placed in holding tanks under casitas in similar water temperatures and conditions to where they were caught. These were tagged and assessed for natural or tag induced mortality and tag loss. Tags to accompany these recorded i) the date, ii) area fished iii) location, iv) sex, v) size CL, vi) reproductive condition, vii) legs missing iii) general comments.

3.2.3 Stock assessment modelling methods of analysis:

A series of analyses of the biological data were conducted and modelling methods were further developed using these data, with the advice of some experts in this field like Dr. Simon de Lestang from WA fisheries department.

Population parameters and fishery data such as catch and effort were assessed and evaluated against environmental and economic variables. The Fisheries Simulation Model FISMO (Chavez, 2006(Ley-Cooper & Chávez 2009) was reevaluated and the depletion model assessment (Sosa-Cordero 2003) that was updated and developed by (Alvarez-Flores & Sosa-Cordero 2010) was also discussed (see Chapter 1). The later models allowed for estimation of fishing mortality, but were constrained in their ability to incorporate tagging data, provide estimates of uncertainty and explore the implications of alternative model structures. So we opted for further developing the brownie model (Brownie et al. 1978) in a more refined modelling framework that is capable of producing estimates of fishing mortality, exploitation rates and biomass of lobsters. The model was used to assess uncertainty of these estimates and their sensitivity to alternative assumptions regarding the life history, movements, migration pulses and distribution patterns of the lobsters, (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014) for details (see chapters 0, 6 and 7).

Modelling framework was extended to consider the implications of a pool of lobsters in deeper water (>20 m) with interchange between the near-shore exploited portion of the stock and the deeper, unexploited portion of the stock (Ley-Cooper et al. 2014). Exploration of alternative patterns of monthly recruitment, changes in monthly vulnerability, and alternative representations of selectivity were also explored (Lipcius et al. 1997). A major benefit of the approach was that it encouraged exploration of the sensitivity of model predictions to inadequacies of current data, and creation of biological reference points (Sissenwine & Shepherd 1987) e.g. using of information on growth derived from lobsters in Cuban waters. It moved the analytical tools closer to the development of a management strategy framework, as suggested by the Marine Stewardship Council certification initiative (MSC). The modelling was developed R template to allow use of more sophisticated statistical tools which were valuable by allowing estimation of uncertainty of predictions (see chapters 0, 6 and 7) (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

3.3 To achieve objective 5 and 6

Field trips to BC and SK to specifically assess live lobster capture, handling, labelling and transportation was carried out in conjunction with the fisher cooperatives, in response to market needs and demands. Data was gathered at the reception centre and results of commercialisation of live lobsters were evaluated. An evaluation was carried out regarding the substitution of fishing gear from gaff/hooks to snare loops as a fishing method changed

during the 2009-10 fishing season in BC (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper 2010). Investigating this process of change in fishing gears included discussion regarding the effects on management, (i.e. undersize and egg bearing female mortality rates), and economic implications regarding post-capture handling, transport from the SK and BC areas to Cancun City, and the relationship with conservation initiatives such as the Chakay and MSC ecolabels.

A semi-structured survey with a series of questions was carried out in order to allow for an analysis of socioeconomic factors. Previous and after effects of socioeconomic variables derived from the new eco-labelling scheme implemented in 2009, such as expenditure, incomes, possible increase in revenue from added value by the new capture methods and processing results were recorded in conjunction with the cooperatives and analysed as part of the project. As a means of investigating their effects on the sustainability of the fishery, an evaluation on price fluctuations, needs for investment in infrastructure, logistics and marketing strategies, as well as current and potential utilities was carried out by closely following the Chakay and MSC eco-labelling commercial schemes.

3.4 To achieve objective 7

Attending workshops, meetings and interviews with all stakeholders including managers, fishers, and scientists, and general public involved in the chain of custody enabled to produce a series of personal and group based recommendations for long term monitoring, assessment and commercial strategies of these fisheries that could lead towards sustainability of the fishery and a are a part of this thesis.

3.5 Ethical Issues

The experimental animals (lobsters) are invertebrates so ethical approval and permits were not required. However, every effort was made to treat the lobsters humanely, they were held with care and in optimum conditions when handling by using shades, clean tag insertion devises and needles. When capturing lobsters from the wild, there was no by-catch and limited environmental impact when installing trial casitas (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán & Lozano-Álvarez 2013).

Assistance from other people in all lobster capture and research tasks were acknowledged in the publications, thesis and/or other published materials.

The questionnaire built for the survey on current socioeconomic status, did not include personal or confidential questions that could offend the interviewed people. Prior to asking the questions they were told the purpose of the study and were asked for their consent. Form C was lodged and approved by the Ethics Committee for this purpose.

3.6 Facilities and Resources

Main facilities used:

Access to the Scientific Stations at BC & SK MPA's, was granted and included the possibility to use general facilities (computer program "R". kitchen, air compressor, etc.), accommodation and diving boats.

Desk, chair, a filing cabinet, computer, access to a printer and photocopies were provided by Curtin University in Australia, UNAM and RAZONATURA in Mexico.

Basic computer software such as Word, Excel, SPSS, and Endnote were used. Models were developed both in Excel (to assist in communicating results to managers) and R, to allow for the use of more sophisticated statistical tools which allowed estimation of uncertainty of predictions.

Two water storage tanks, enough for holding up to of 8 m³ seawater. Two 12 m³ water tanks on a re-circulating system for holding lobsters for up to two weeks at a time were used.

3.7 Data Storage

Support for gathering historical data and fishery data in the field work with the fisher cooperatives were conducted through the cooperatives, Integradora de Pescadores de Quintana Roo and sub-delegación de Pesca de Quintana Roo/CONAPESCA.

All raw data collected from trials were entered initially into Excel and SPSS statistical package. All data and statistical analysis was then be placed onto CD's external drives, and held at the Research Unit, and Backups made at the cooperatives. Data was stored on cloud, hard disks and external drives at Curtin and UNAM, as well as in a lockable filing cabinet (CD's and written data) and will be held for at least 5 more years, to which only ASRU staff will have access.

4 CHAPTER 4 Use of Artificial Shelters (“Casitas”) as an Alternative Tool for Stock Evaluation and Management of *Panulirus argus* in Banco Chinchorro (México)

Note: The core structure and contents of this chapter were published (Ley-Cooper et al. 2011), under the same title in the Proceedings of Gulf and Caribbean Fisheries Institute GCFI-2011. To comply with the current format and structure of this thesis and to avoid repetition, some contents and figures have been modified or updated from the original version, new references have been included, and some maps and definitions are referred to in the literature review section (chapter 1). Some recent outcomes of the project which have occurred since the date on which the paper was published in 2011, have also been included and discussed.

4.1 INTRODUCTION

Spiny lobsters (*P. argus*) are a valuable fishing resource throughout the wider Caribbean region, yet along most of the MBRS large reproductive adults of *P. argus* are being increasingly depleted (Ehrhardt & Fitchett 2010). Because egg production increases non-linearly with female size (Fonseca-Larios & Briones-Fourzán 1998), and large females require sperm from large males to fertilize each clutch of eggs (MacDiarmid & Butler 1999), removal of large reproductive adults may impact the production of larvae (Bertelsen & Matthews 2001a). It is a fact that in BC the fishery for *P. argus* has historically targeted large reproductive adults (Lozano-Álvarez 1994, Sosa-Cordero 2003, Ley-Cooper 2006, Ley-Cooper et al. 2011), and this is why management measures and ideas to counteract this trend have been proposed and discussed recently (Ley-Cooper et al. 2011).

As in Ley-Cooper et al. (2011), in this chapter I analyse and review the potential benefits of the initiative to implement casitas and a campo management scheme in Banco Chinchorro (BC), as well as propose a permanent research and monitoring program from a current and updated perspective. The casita initiative started in 2010, and has been a joint effort promoted by an inter-institutional steering committee which was established to propose alternative fishing practices, suggest management measures and take actions for attaining sustainability of the *P. argus* fisheries in BC and SK (Ley-Cooper et al. 2011) (MRAG-Americas 2013). As previously discussed in Ley-Cooper et al. (2011), the aim of the initiative is to assist the fishing cooperatives in improving management of the *P. argus* lobster fishery in BC through the deployment of “casitas” as a strategy for increasing lobster

biomass in habitat areas where natural shelters and refuge for lobsters are scarce, as is most of the northern segment of the lagoon in BC between Cayo Centro and Cayo Norte (see Figure 1-3, Figure 1-4 and Figure 1-5).

Casitas are large artificial shelters that harbour the full size range of lobsters (Lozano-Álvarez et al. 1991b, Sosa-Cordero E. et al. 2008) (see description in section 1.6.4.1.1). Casitas were first used for harvesting lobsters in Cuba (Baisre 2000, Cruz & Phillips 2000), then in Mexico (Briones-Fourzán et al. 2000) and then after in Bahamas (Deleveaux & Bethel 2002). In Mexico, casitas are extensively used in the two large bays (BA and BES) that form part of the SK (see section 1.2.2.). The fishing cooperatives that operate in BA and BES bays have devised an organizational scheme that has rendered the fishery remarkably sustainable (Lozano-Álvarez et al. 1991b, Briones-Fourzán et al. 2000, Defeo & Castilla 2005, Sosa-Cordero et al. 2008, Gardner et al. 2013). This scheme consists of the partitioning of the fishing areas in the bays into parcels “campos” allotted to individual fishers (details in section 1.6.4.1.2). In SK a fisher does not own his campo (as this is forbidden by law) but is free to deploy within his campo as many casitas as he is willing to invest in, and hence he owns the casitas. On average, there are 3.3 casitas/ha in individual campos with distances between casitas varying from 25 m to over 50 m (Lozano-Álvarez et al. 2003). As reviewed in Section 1.6.1, using diving masks and snorkels, the fishers survey the casitas and extract the lobsters with hand nets and snares. Federal regulations include a minimum legal size of 135 mm abdominal length (~74 mm carapace length on average), a 4-month closed season (March 1 to June 30), and a prohibition on capturing ovigerous females as well as on using gaffs or hooks to extract lobsters. Internal regulations of the cooperative forbid fishing in someone else’s campo, as well as the use of SCUBA or hookah diving (Sosa-Cordero et al. 2008).

The casitas/campo system has not been previously implemented in BC. However, in a study conducted between 2005 and 2007, 56 experimental casitas were deployed in the atoll lagoon of BC to study growth, movements, and prevalence of *P. argus* lobsters with the PaV1 disease (Ramírez-Estévez et al. 2010). In total, 1060 lobsters ≥ 20 mm carapace length (CL) were marked and 404 (38%) were recaptured. Distance moved by individuals (measured over a straight line) varied between 11 m and 4.2 km, with some extreme movements of 16, 19, and 37 km. This is the only documented information on the previous use of casitas in BC.

Given the geographic isolation of BC (see 1.2.1), the atoll is prompt to function as large control site for studying and monitoring benthic species, fished populations and ecosystem changes linked to these. The fact that no operations of large magnitude (i.e. installation of >900 casitas) have been conducted before in BC, the initiative to implement these on a larger scale represents an excellent opportunity to obtain scientific data for analysing the effects that casitas may have on the local *P. argus* population dynamics, and the fishery itself (Sosa-Cordero et al. 1999, Briones-Fourzán et al. 2000, Sosa-Cordero 2003, Briones-Fourzán et al. 2007, Ley-Cooper et al. 2011, Ley-Cooper 2013). The measurement of juvenile recruitment and survival linked to casitas, rate of occupancy of seagrass and hard bottom habitats and any possible changes in the local lobster stock are all possible outcomes from a study of this nature.

Similarly to the studies carried out by Briones-Fourzán et al. (2000), Briones-Fourzán et al. (2007) and by Ramírez-Estévez et al. (2010), parallel to the casita implementation plan in BC, a research and monitoring program must be in place for gathering data on lobster growth, natural and fishing mortalities, movements, changes in abundance, and presence of the PAV1 disease. Information on these aspects should be obtained in order to support future risk and stock assessments (Fletcher 2005), and facilitate stakeholder decision-making for evaluating the potentially new management scheme (Penn et al. 2015). Considering preliminary results and information obtained from the small-scale pilot study conducted in 2009–2010 (Ley-Cooper 2009), the larger project to deploy > 900 casitas is still in progress to date, . the assumption being that casitas will enhance the lobster population in BC (Briones-Fourzán et al. 2007), and changes in abundance and juvenile survival are expected to occur, which certainly should be monitored and assessed (Briones-Fourzán & Lozano-Álvarez 2013).

A financial projection for BC was previously carried out by Ley-Cooper et al. (2011) based on knowledge regarding the average number of lobsters (kg) harvested per casita, derived from studies carried out in Puerto Morelos, BES and BA in SK (Lozano-Álvarez 1992, Lozano-Álvarez et al. 1993, Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007, Ley-Cooper et al. 2013). In general terms the financial estimates predicted that the casita implementation will improve the economic revenue of the fishers in the near future (Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper et al. 2011). Information on this regard is detailed and presented, as well as ideas of where the campos could be potentially established and casitas could be deployed in BC. In similar terms

to Ley-Cooper et al. (2011) the number of casitas to be deployed, the number of lobsters likely to be found in casitas, how the use of casitas will likely affect the effort and rate at which lobsters are harvested in BC are some themes that are discussed in this chapter, as it is expected that the analysis will help define future management action plans in BC and other sites in the MBRS.

4.2 Study Site

A complete and detailed description of the Banco Chinchorro (BC) study site can be found in Chapter 1 of this thesis, under the subtitles: “Description of the study areas” section 1.2; Banco Chinchorro (section 1.2.1). So this section has been excluded from this section of the thesis to avoid repetition, because it has been presented beforehand as in the original paper Ley-Cooper et al. (2011),

4.3 The lobster Fishery at Banco Chinchorro

The fishery for *P. argus* has historically been the main economic activity for the communities that make use of BC, and fishing for lobsters is restricted to licensed fishing cooperatives (see review from sections 1.6.1 to 1.6.5). The lobster fishers are organized into cooperatives that obtain a 20 year fishing concession with annual renewals. In BC, three cooperatives have rights to fish for lobsters (details in section 1.6.5.) Cooperatives must comply with the current fishing regulations which include a closed season from 1 March to 30 June, a minimum size of 135 mm tail length (~74 mm carapace length, CL), and a prohibition on capturing egg-bearing females, amongst other rules and regulations (details in section 1.6.1).

As has been evidenced by data base sources of catch records from governmental agencies (CONAPESCA-SAGARPA 2013), as well as by previous studies (Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010), lobster landings in BC have been relatively stable during the last two to three decades. Catches have fluctuated around 25- 30 t tail weight (TW) (Figure 4-1), which is approximately equal to 65 t whole weight (WW) when using local length weight conversions. Contrary to patterns observed in other Caribbean fisheries (FAO 2001, de León et al. 2005, Ehrhardt et al. 2010a) these catches have been achieved without an apparent increase in effort.

The increase in catch records from 25 t (TW) average before 2010, to the current \approx 65t (WW) in 2015, has mainly been attributed to the conversion of fishing practices and sales of whole/live lobsters (WW) instead of lobster tails (TW) (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009); because fishing practices in reef habitats using hooks/gaffs have been eliminated and completely replaced by using snare loops instead. This implies that the lobsters head which \approx 2/3 of the animals whole weight (WW) is no longer wasted, which therefore has increased the landings values recorded before 2010 by three times.

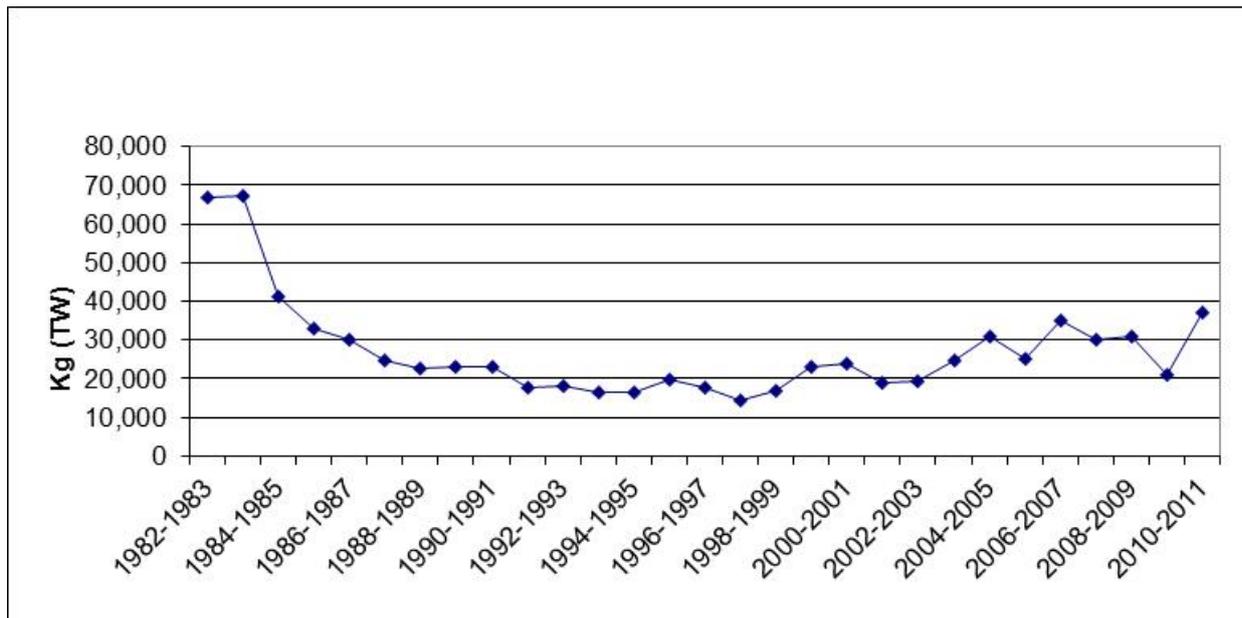


Figure 4-1: Graph showing Caribbean Spiny Lobster (*P. argus*) seasonal catches for the Banco Chinchorro Biosphere Reserve fishery. It includes catch data from the three Cooperatives which are entitled to exclusive concession rights over the BC fishery. On the “Y” axis total catches (kg) are represented in lobsters tail weight (TW). “X” axis represents 29 fishing seasons on a yearly scale; 1st season begins July 1982 and ends February 1983, and the last 29th season begins July 2010 and ends February 2011.

The catch of the lobsters is mainly carried out in coral reef habitats and is limited to shallow depths (< 20 m), since skin diving using snare loops, mask and snorkel without alternative air source equipment is the only method for fishing lobsters (López & Consejo 1986 , Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998),(Lozano-Álvarez et al. 1991b, Sosa-Cordero 2003, Ley-Cooper 2006, Ley-Cooper & Chávez 2009, Ley-Cooper et al. 2014). Fishers mainly fish on and near the reef and sponge patches towards the southern end of the BC lagoon, and around the reef break which surrounds most of the atoll (González-Cano et al. 2000a, Ley-Cooper 2006), where depths

vary between 3 m and 15 m (Borges-Souza 2011), and there is a larger number of natural refuges for lobsters created by the higher density coral reef habitats and sponge patches (Carricart-Ganivet et al. 2002 , Contreras-Silva et al. 2012), which increase the possibility of finding juvenile and adult *P. argus* lobsters as they are essential habitats for them (see Figure 1-3)(Ley-Cooper 2006, Briones-Fourzán & Lozano-Álvarez 2013).

Previous studies carried out in Mexico Q.R. indicate that in BC local environmental factors, patterns of recruitment, and growth rates of lobsters may have helped to sustain the current stock sizes and catch rates (Lozano-Álvarez 1992, Sosa-Cordero 2003, Ley-Cooper 2006, Chávez & Ley-Cooper 2007, Alvarez-Flores & Sosa-Cordero 2010, MRAG-Americas 2013). Similarly to what occurs in BES and BA- SK (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), monthly catch patterns are repeated on a yearly basis from one season to the next (see

Figure 4-2). The starting months of the fishing season July/August present the highest peaks in catch numbers, which gradually diminish as the season progresses towards the end of autumn (October and November), after which a smaller increase in catches occurs (Ley-Cooper 2006, Ley-Cooper & Chávez 2009). The autumn peak could possibly be indicating recruitment (see

Figure 4-2), and will be further discussed in section 4.5

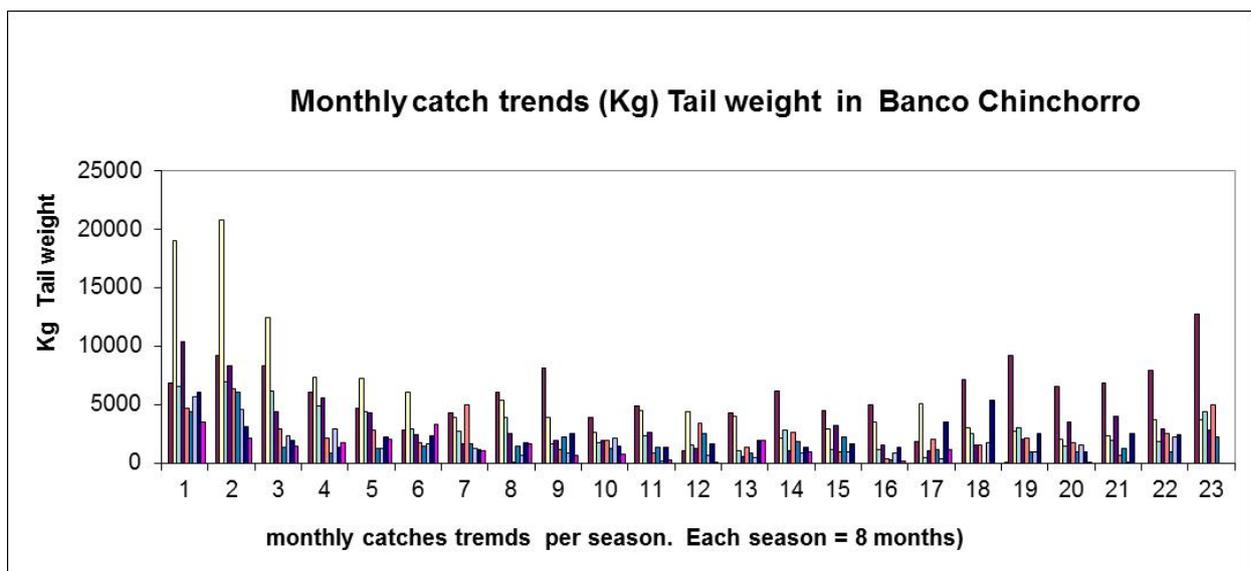


Figure 4-2: Bar graph showing *P. argus* monthly catch trends (Kg), expressed in tail weight (TW) on the “Y” axis for each fishing season (1-23) on the “X” axis, which correspond to

years 1982 to 2004, for the Banco Chinchorro Biosphere Reserve fishery. It includes catch data from the three Cooperatives which are entitled to exclusive concession rights over the fishery. The pattern is recurrent almost every year (1-23), showing the highest catches occurring during the start of the fishing season for the months of July and August, and then a small peak towards the end between November and February.

4.4 Deployment of casitas in BC

In Q.R. Mexico, experimental studies by (Briones-Fourzán et al. 2000), Briones-Fourzán et al. (2007) have produced evidence in favour of deploying casitas into areas where refuge is scarce in BC, such as in the seagrass, hard bottom and sandy areas in the northern segment of the lagoon (see Figure 1-3, Figure 1-4, and Figure 1-5). In accordance with the recent review published by Briones-Fourzán and Lozano-Álvarez (2013), some benefits of introducing casitas would be that: (a) casitas increase survival of lobsters because they allow for cohabitation of small juveniles, which are more vulnerable to predation, with larger conspecifics that have greater individual and collective defensive abilities (Briones-Fourzán et al. 2007), (b) casitas allow lobsters to exploit the available food resources in a more efficient way, reducing their time of exposure to predators (Lozano-Álvarez 1995), (c) because casitas are deployed far from the coral reefs, their use reduces impact of fishers on the reefs and on the large reproductive adults that dwell in these habitats, and (d) casitas allow for selectivity in size and maturity of lobsters, which can be harvested (and sold) alive, adding economic value to the product (Ley-Cooper & Garcia-Rivas 2009).

The recommended way of introducing casitas into BC would be by predefining a campo system in participative workshops as described by (Velez 2014), where cooperative fishers would also be consulted and decide upon the management measures, together with authorities, in a bottom up approach for decision making. Rules and conditions should consider territorial rights (Gardner et al. 2013) similar to those existing in the SK cooperatives, or probably simply be replicated. Co-vigilance strategies between park rangers (CONANP), fishery authorities (CONAPESCA) and fisher cooperatives would be improved by the campo system, as it is bound to work more efficiently and with less conflict (Briones-Fourzán & Lozano-Álvarez 2013).once rules are set which allow for semi-ownership of casitas and promote self-surveillance, For the past few years, efforts to discourage the sale of lobster tails and encourage the fishers to catch live lobsters in BC have been made (Ley-Cooper 2009). The most recent campaign was under the theme “live lobsters are worth

more” which promoted new fishing practices, as well as the handling, storage and transport of the live lobsters by: a) the use of snares and hand nets to catch lobsters (instead of using gaffs); b) a fishers exchange program whereby cooperatives from BC were trained by other fishers from SK to handle live lobsters on boats; c) the building of artisanal cages of free flowing water and finally d) the construction and deployment of casitas constructed from recycled wood: (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009).

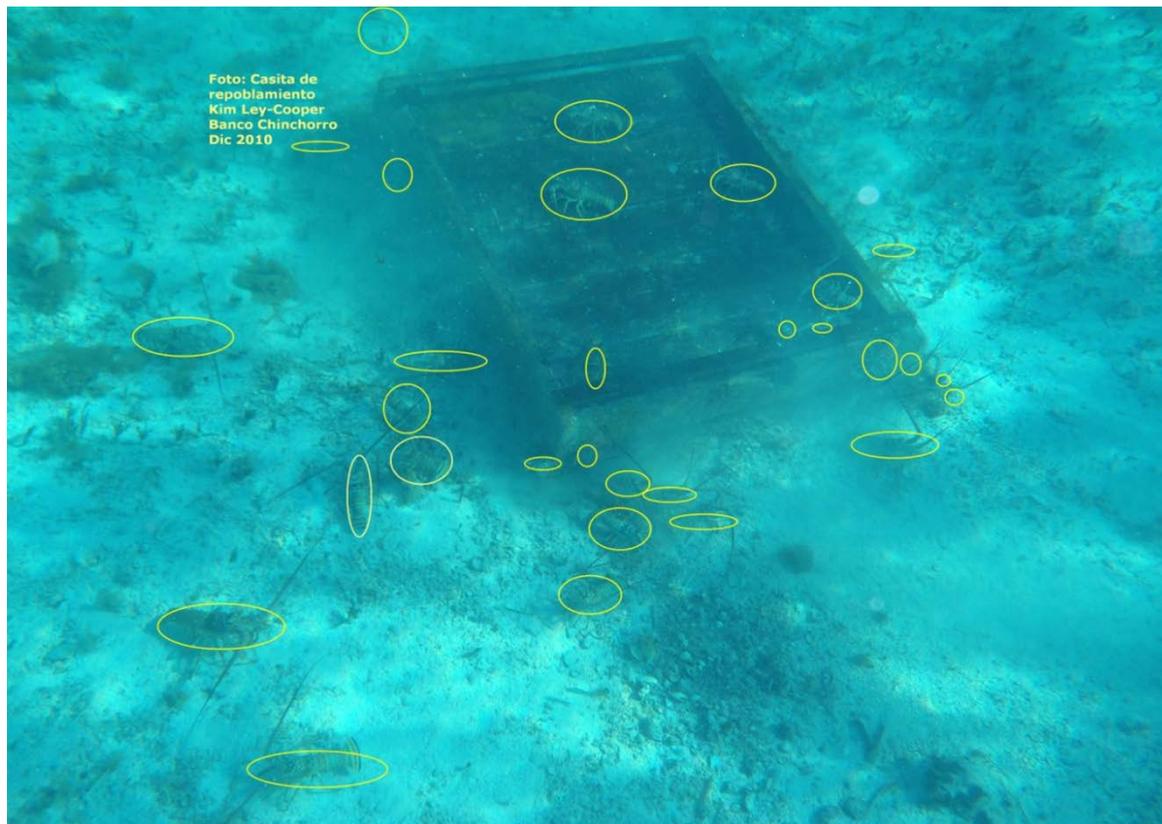


Photo 4-1: A casita designed for deployment in Banco Chinchorro, made from heavyweight hard recycled wood from Q.R. (“Zapote”) during 2010. These were originally deployed near Cayo Centro in BC. Each yellow circle illustrates one of the thirty juvenile *P. argus* lobsters which were found under the casita using it as a refuge. Lobsters were photographed outside, only after the casita was lifted for research/monitoring and tagging purposes.

Seventy casitas were constructed from this hard wood known as Zapote. (see Photo 4-1) for the pilot study (Ley-Cooper 2009). Deployment was conducted between the 2009 and 2010 fishing seasons, and most of these casitas were placed on seagrass and hard bottom sandy areas within the BC lagoon where fishing is allowed (Figure 1-2 and Figure 1-3). Some other casitas were deployed as a control site in the no-take zone (“zona nucleo”) near Cayo Centro where the CONANP research station is located, thus providing an experimental area

for tagging and recapture of lobsters in the absence of fishing. The casitas were deployed 50 m separated from each other in order to form a 50 x 50 m square grid, following the recommendations from previous studies (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007, Zapata-Araujo et al. 2007).

In a first workshop carried out between fisher cooperatives, NGO's, authorities, researchers and various stakeholders, boat captains were encouraged to select an area within the BC lagoon to be assigned as a personal campo with the given rights and obligations. Originally campos were meant to be allocated for exclusive use by each of the individual boat captains, from each one of the three cooperatives that operate in BC. However, currently the idea is that areas in BC should first be delimited and assigned to one of the three cooperatives, and subsequently subdivided to each associated fishers or boat captains in order to make the rules and compliance easier for the near future.

In the 2010 pilot experience casitas were left to soak for at least one month before being checked and monitored for the presence of lobsters, where biometric data, tagging and release of all undersized and egg bearing lobsters was conducted when possible. Members from the three fishing cooperatives collaborated with collecting historical and logbook data. This included biological information such as CL, weight, sex, and sexual maturity of each lobster caught, and fishery dependent data such as effort per trip. In order to determine CPUE, the number of fishers per boat, number of casitas and number of sites fished per day were recorded. Data derived from research logbooks was to be compared and complemented with information provided by the cooperatives and by the fisheries department. The idea was that data could be processed using change-in-ratio techniques for estimating catchability, indexes of lobster removals, or similar indirect methods for estimating population sizes (Melville-Smith & de Lestang 2006, Pollock et al. 1985).

Unfortunately not enough data in this regard was gathered due to the unfavourable meteorological conditions generated by Hurricanes Rina and Ernesto that hit BC during the timeframe of the study (Ley-Cooper 2013). The process of installing up to 900 casitas was provisionally suspended due to the impact that these hurricanes had on BC, which destroyed most of the wooden casitas that had been installed or were yet to be assembled. Currently in progress in 2015, the casita initiative has continued, following a change from wood to cement in the design, inspired in the SK experience (see section 1.6.4.1.1).

The larger project which commenced in 2010, has essentially followed the same protocol used in the pilot study and uses recommendations from the studies by Briones-Fourzán et al. (2000) and Briones-Fourzán et al. (2007). Fishers and authorities were encouraged to develop the project based on the financial projection, which estimated a yield of at least 3 kg of lobsters per casita, based on results presented from the previous studies carried out in Q.R. by Briones-Fourzán et al. (2007). As enlisted by Briones-Fourzán and Lozano-Álvarez (2013) all benefits from installing casitas are expected to occur in BC, and the main hypothesis is that casita implementation will potentially provide a significant increase in the local *P. argus* population, by essentially “enhancing juvenile survival rates” (reducing mortality) and therefore, economic returns to the fishers will also eventually increase.

Table 4-1: From Ley-Cooper et al. (2011), shows the projection of total catches estimated for only one of the three Cooperatives (SCPP Banco Chinchorro), based on the assumption that the recruitment patterns stay stable and the current yearly landings from reef habitat areas are maintained, so that, catches derived from installing the casitas increase total landings at a 5.6% rate per year.

| Projected yearly estimated increase in lobster catch (kg) with the use of casita for the BC cooperative | | |
|--|-------------------------|--------------------------|
| | Tail weight (kg) | Whole weight (kg) |
| Year 1 | 16,070.0 | 48,210.0 |
| Year 2 | 16,969.9 | 50,909.9 |
| Year 3 | 17,420.2 | 53,460.7 |
| Year 4 | 18,395.7 | 55,187.2 |

As described in Ley-Cooper et al. (2011), the preliminary projections carried out for BC were based on a conservative estimate of an average lobster harvest rate of at least 3 kg (whole weight) per casita per fishing season. The assumption was that approximately 2,700 kg per season of live lobsters will be harvested if the 900 casitas are installed appropriately in

BC. Based on the catch statistics obtained during 2009 season, by only the “Banco Chinchorro” Cooperative, catch would therefore increase by 5.6% (

). Considering a dock price of \$380 MXP per kg of lobster tail and of \$200 MXP per kg of live lobster, this would mean an income increase during the first year of the casita operation system of \$342,000 MXP (5.6%) if lobsters harvested from casitas were sold as tails, and \$540,000 MXP pesos (8.8%) if lobsters harvested from casitas were sold alive, which is the recommended strategy.

4.5 Research and Monitoring program including tagging and recapture techniques for analysis in BC

The relative stability in total catch patterns which have been observed in BC for the past three decades (shown in Figure 4-1 and Figure 4-2), constitute only one very general indicator of sustainability for the local *P. argus* population (MRAG-Americas 2012, 2013). In relation to stock and environmental sustainability (Marine Stewardship Council 2010), further studies must be carried out (Thomson & Caputi 2005, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014, Penn et al. 2015). To improve upon existing stock assessments of the BC fishery (Sosa-Cordero 2003, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010), we must better understand recruitment processes, exploitation rates, and local population dynamics. Stock assessments for instance should ideally include both catch data and a detailed analysis of catch rates (CPUE) (Walters 2000, de Lestang et al. 2009, Goñi et al. 2010, de Lestang et al. 2012), as well as an evaluation of specific biological characteristics and behaviour of the local population (de Lestang 2014). Furthermore, fishery independent data must be gathered, information must be systematically monitored, revised, and analysed scientifically and on a yearly basis (Bellchambers et al. 2009, de Lestang et al. 2012).

A tagging study carried out by Ley-Cooper et al. (2014) in the deep unfished areas (>20 m) in SK, indicated that a small recruitment peak occurs as an increase in catch rates is recurrently observed towards the end of the fishing season, during the autumn months (October November). The latter has been partially attributed to a percentage ($\approx 15\%$) of lobsters moving from the deep unfished areas into the shallow areas subject to fishing (Chapter 6), possibly incited by changes in environmental conditions and the presence of Nortés (see chapter 7). Using the methodology described in Chapter 6 Ley-Cooper et al. (2014), an analogous tagging study in BC would be needed to confirm that a similar recruitment process occurs from the deep (>20 m) to the shallow areas (< 20 m) within the

BC lagoon. However, it seems likely that the recruitment process observed in BES SK also occurs in BC, since similar yearly catch and CPUE trends are observed in both areas (Sosa-Cordero 2003, Alvarez-Flores & Sosa-Cordero 2010).

Considering the above, it is feasible to assume that the exploited portion of the population found < 20 m in BC could be partially sustained by recruiting a percentage of the unfished portion of the adult stock which initially escapes exploitation in the deep >20 m unfished areas (Ley-Cooper et al. 2014). Some empirical evidence exists that could indicate this recruitment process from the deep also occurs in BC as: 1) large adult lobsters which probably escaped the fishery during the closed season (March to June) are fished in the shallow (<20 m) habitats throughout the fishing season, including the final months from December to February, well after fishers have depleted most of the stock subject to exploitation in the shallow areas during the months of July, August and September when catches peak (see

Figure 4-2); and 2) lobsters being recruited to the fishery by growing from an undersized illegal juvenile to a large adult size within a 3 month period (from July to October), seems unlikely (see section 1.4.2.1.1), due to the number of moults and timing required to reach the large sizes that are caught in BC during autumn.

Following the change in design from wooden to cement casitas, the implementation project should be complemented by a permanent research and monitoring program which in turn should include a tagging campaign to evaluate the relationship between the stock subject to fishing (at depths ≤ 20 m) and the stock that escapes fishing (>20 m) (Ley-Cooper et al. 2014), to help estimate fishing mortality with empirical data (Ley-Cooper et al. 2013, Harford et al. 2015). The tagging protocol for the main project in BC should be similar to a tagging protocol implemented in Bahía del Espíritu Santo SK (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). Briefly described, lobsters should be measured (CL, mm), sexed, examined for sexual maturity and missing limbs, and tagged with Australian “Hallprint” T bar tags, applied ventrally. Once a lobster has been measured and tagged with the least exposure to sun and outside the water it should immediately be placed back into the water and released under the casita, where the GPS position should be recorded.

One of the major knowledge gaps in assessing the total stock of the BC fishery is the relationship between the abundance of lobsters in shallow (≤ 20 m) and deeper (>20 m) habitats. The relative abundance and proportion of the *P. argus* population found in both

these habitats is fundamental for understanding the fishery, and is the main reason for tagging adult lobsters in the deeper areas as well as in the shallows (Ley-Cooper et al. 2014). These lobsters should be caught beyond the reach of the skin-diving fishery (>20 m) and released as near as possible to their point of capture. These tagging activities should be conducted at different sites distributed between the north, south, western and eastern locations of BC.

As in Ley-Cooper et al. (2013) and Ley-Cooper et al. (2014) the combination of casita and reef skin-diver based surveys will provide complementary results that will allow a more comprehensive examination of abundance, size distribution and migration patterns across all size classes, and in most areas of BC. This research will also allow an assessment of movements, timing, and growth of recaptured lobsters throughout the year (Bertelsen 2013, Harford et al. 2015). The tagging programs should be advertised widely and a reward program should be introduced to encourage tag returns (Ley-Cooper et al. 2013).

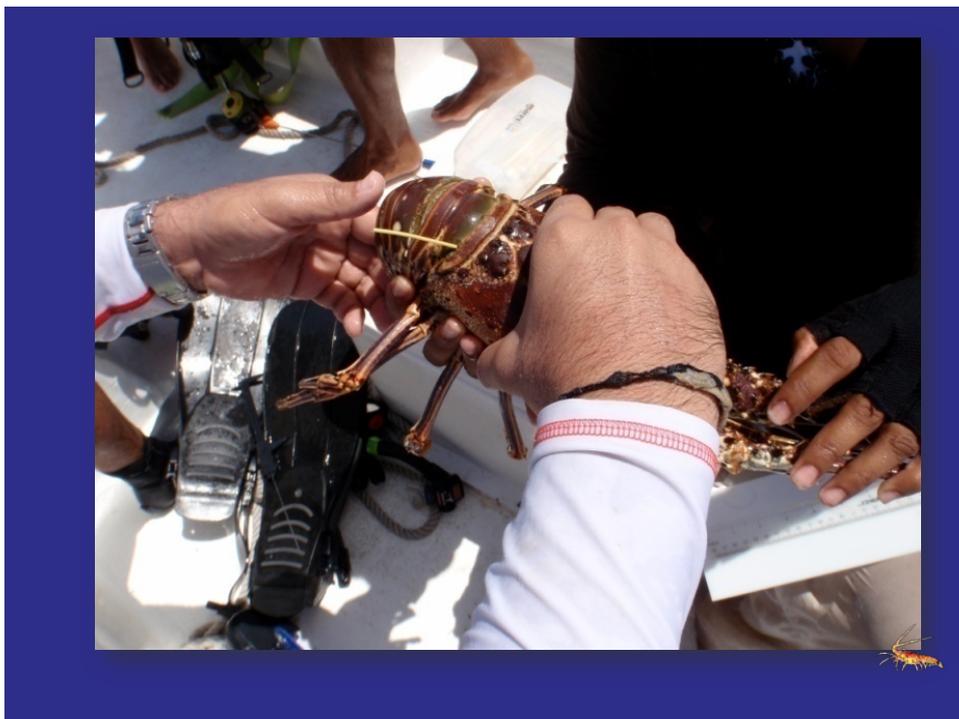


Photo 4-2: A lobster (*P. argus*) tagged in the dorsal area with a T bar, for assessing fishing (F) and natural mortality (M), as well as movements and migration patterns at Banco Chinchorro.

4.6 Progress to date

The construction of the first lot of wooden designed casitas commenced in June 2010. As the process of designing and constructing casitas was conditioned to be from sustainably

certified recycled wood, of a nearby forestry community, it took longer than expected. The locations of the wooden casitas deployed in 2011 are shown in Photo 4-1. By September 2011, approximately 60 casitas had been deployed in the fishing areas where campos were proposed by fishers from the cooperatives, and approximately 40 casitas were installed in the no- take areas. By the end of 2013, a total of 900 wooden casitas was projected to be built and installed. However, as mentioned previously, bad weather conditions, strong under currents, the use of non stainless steel material and the passage of hurricanes Rina and Ernesto destroyed most of the casitas that had been constructed (Ley-Cooper 2013). During the course of 2015-16 new casitas made of cement are expected to be installed to substitute the latter.

P. argus lobsters tagged were 437 (32.0–152.3 mm CL) both from casitas and the deep reef habitats (52% males and 48 % females). Out of these lobsters, 22.6% were of sublegal sizes and 77.4% of legal sizes. The largest lobsters, ranging from 140 mm to 152.3 mm CL, were caught in the deep habitats over the east side of BC. Most of the lobsters tagged in casitas were <78 mm CL (i.e., sublegal), and most of the larger lobsters were tagged in the deep habitats out of reach of free diving (>20m). There has been a very low reporting rate of recaptures, and most recaptures have been obtained in the no-take areas by research staff and park rangers.

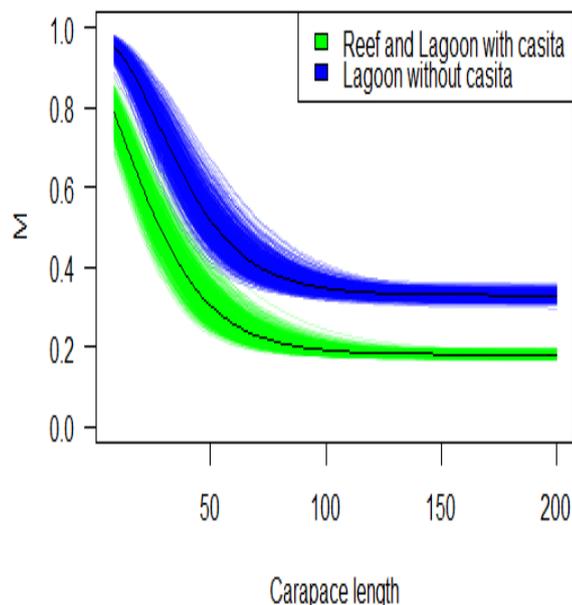


Figure 4-3: shows two black lines representing trends predicted for natural mortality “M” for *P. argus* lobsters in BC at different sizes (CL). The mean and standard deviation for natural mortality were estimated by the model under two scenarios: 1) “green” the reef and lagoon

ecosystems in BC after installation of 900 casitas; and 2) “blue” lagoon in BC without any casitas installed, hence the current situation. Ley-Cooper, K and de Lestang, S. produced the modelling projection of based on biological data and tagging experiments obtained from BC, and published information by Briones-Fourzán et al. (2007) regarding survival rates in casitas.

As has been verified by the recent evaluations carried out for the MSC certification process (MRAG-Americas 2012, 2013), the BC lobster’s fishery steering committee is composed of representatives from the fishing cooperatives, government agencies, universities, research institutions and NGOs, that meet periodically to discuss management issues. This practice has been a positive outcome encouraged, to a certain extent, by the Chakay initiative and MSC eco-labelling process. However, it has been evident that since the idea of implementing casitas in BC was launched in 2011 (Ley-Cooper et al. 2011), the initiative has advanced more slowly than was expected, due to financial difficulties and logistics, including the passage of the two Hurricanes previously mentioned (Ley-Cooper 2013). Arguably both the fishers, authorities and steering committee could have played a more active role in implementing casitas and/or proposing other management measures by annually carrying out a structured risk assessment methodology to define goals and objectives (Fletcher 2005), as well as by leading and assessing the fishery with a permanent research and monitoring program (Bellchambers et al. 2014), as occurs with other lobster fisheries around the world (Penn et al. 2015).

DISCUSSION

Casitas are mostly used to harvest lobsters for commercial purposes. However, in Ley-Cooper et al. (2011) and this study, casitas are also proposed as an experimental tool for carrying out stock assessments, for providing useful data to examine juvenile growth and survival rates associated to the instalment of artificial refuges, and to evaluate *P. argus* movement patterns in BC, as well as natural and fishing mortalities at several sizes/age groups (Ramírez-Estévez et al. 2010). A casita implementation program in BC may open the possibility for carrying out further behavioural studies for *P. argus* and associated predator species (Briones-Fourzán & Lozano-Álvarez 2013), Gutzler et al. (2015), and to better understand *P. argus* fishery dynamics in BC, the MBRS and in the wider Caribbean, where casitas are programmed to be implemented or are currently in use.

Most importantly, in BC casitas represent a potential instrument for spearheading the implementation of a new campo fishery management system, inspired by the positive experience from BES and BA in SK which allocates rights and concessions to the fishers in a semi-ownership arrangement. Besides the socioeconomic aspects, a study of this nature will help evaluate the impact casitas have in: a) enhancing the local *P. argus* stock through an increase in survival (Briones-Fourzán et al. 2000, Briones-Fourzán et al. 2007); b) reducing fishing effort on reproductive adults and c) mitigating the impact on coral reef habitats in the BC shallow habitat areas (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper et al. 2011).

A habitat analysis for campo distribution and *P. argus* abundance should be carried out before instalment of casitas. The potential of casitas to enhance the lobster stock in BC is to be analysed from the initial stage, once the cement casitas are installed. Lobsters of all size ranges will most probably colonize underneath them, once the casitas have been in the water for a month or so (Ley-Cooper 2009, Ley-Cooper et al. 2011). Campos and casitas should be evaluated periodically, and it is recommended that at least large reproductive and egg bearing females and undersized (<135 mm CL) lobsters should initially tagged throughout the whole season and the closed season, to evaluate the progressive impact/increase on the local population (Ramírez-Estévez et al. 2010).

Previous studies have shown why casitas deployed in no-take areas could help better understand their impact in BC, without the possible interference portrayed from fishing mortality (Briones-Fourzán et al. 2007, Briones-Fourzán & Lozano-Álvarez 2013). Predation is a main cause of mortality of young juvenile lobsters (Butler & Herrnkind 1997, Gutzler et al. 2015) because defence strategies such as the use of their spiny antennae to fend off predators (Briones-Fourzán et al. 2006) are not very efficient in small juveniles (Childress & Herrnkind 1997). However, coordinated group defence within a refuge is a social behaviour of *P. argus*, and has been documented as an efficient counter attack against predators (Herrnkind et al. 2001, Briones-Fourzán et al. 2006), and to considerably diminish mortality per capita (Eggleston & Lipcius 1992, Briones-Fourzán et al. 2007). It is expected that extensive sea-grass areas where natural refuge is scarce and heterogeneously dispersed, as is the case in the atoll lagoon of BC, casitas will be able to serve as refuge and to increase lobster gregariousness (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán & Lozano-Álvarez 2013).

Since *P. argus* lobsters undergo ontogenetic habitat shifts, lobsters will eventually abandon the “casitas” as they grow, but other smaller lobsters will recruit into the casitas, potentially resulting in a production increase (Arce et al. 1997, Sosa-Cordero et al. 1998, Briones-Fourzán & Lozano-Álvarez 2001a). Based on the success of the casita-based fishery in the bays of Sian Ka’an (Lozano-Álvarez et al. 1991b, Arceo et al. 1997, Sosa-Cordero et al. 1999, Sosa-Cordero et al. 2008), a responsible use of casitas within a well-regulated and managed fishery is recommended for the cooperatives in BC (Briones-Fourzán & Lozano-Álvarez 2013).

Open-access fisheries without many regulations or defined territorial rights (Gardner et al. 2013), which exist in other areas of the Caribbean, are progressively leading to potential collapses (Caddy & Seijo 2005), and replicate a typical example of a “tragedy of the commons” (Hardin 1968). In contrast, we witness the operation of management systems in SK and BC Biosphere Reserves, where governance and enforcement of the MPA’s regulations by the CONANP and CONAPESCA authorities exist, and the cooperatives participate in regulation. The casitas/campo system established in the BA and BES bays of SK, are largely self-regulated by the cooperatives, and constitute a distinct lobster harvesting technique, since they virtually divide the sea floor into a series of parcels given out as territorial ownership to individuals for a better management of the resources within them (Sosa-Cordero et al. 2008). Based on knowledge obtained in previous studies carried out in SK and in other Latin American countries such as Cuba, preventive measures for reducing fishing effort and pressure on reproductive adults in BC could include a controlled deployment of casitas that are not to be fished in the far northern area of the BC lagoon where mostly seagrass habitats are found (Carricart-Ganivet et al. 2002, Borges-Souza 2011, Contreras-Silva et al. 2012).

There is a series of factors that could affect the expected results from casita deployment which include: a) biophysical features related to the ecosystem including oceanographic dynamics, currents, and temperatures (Butler et al. 2008, Butler et al. 2011, Muhling et al. 2013); b) changes in environmental factors such as wind effects, rainfall and climate (Caputi et al. 2013, Puga et al. 2013)(see chapter 7) that could affect distribution and lobster occupancy levels in casitas; and c) aspects related to the general biology and behaviour of the *P. argus* species including recruitment, growth, ontogenetic movement and migration patterns to and from the deep (>20m) (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), feeding patterns, and the search for essential natural habitats (Briones-Fourzán &

Lozano-Álvarez 2013), are all factors that could change after the instalment of the casitas, and are all unknown variables yet to be assessed.

The effects of casita deployment in BC should ideally be assessed comprehensively and from a bio-economic stand point in order to readily address management issues and carry out risk assessments derived from their instalment (Donohue et al. 2010, Gardner et al. 2013, Bellchambers et al. 2014, Penn et al. 2015). Some important data to be gathered and assessed should include: estimates of age of first capture; changes in fishing effort (CPUE) and abundance throughout the fishery (Sosa-Cordero 2003, Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010); juvenile survival rates in and outside casitas (Briones-Fourzán & Lozano-Álvarez 2001a); presence of reproductive adults and egg bearing females in casitas (Sosa-Cordero et al. 1998); monitoring of the effects that casitas may have on juvenile and large reproductive adult lobsters in terms of recruitment to and from the fishery; as well as exploitation rates; and movement and migration patterns to and from the regular reef habitats found in the southern areas where casitas are not projected to be deployed.

Further research should be carried out to evaluate the effects of the casitas especially if the certification with MSC is to be continued (MRAG-Americas 2013). Previous research has suggested that fishing mortality and effort based on current fishing practices should not be increased in BC (González-Cano et al. 2000a, González-Cano et al. 2000b, Sosa-Cordero 2003, Ley-Cooper 2006, Ríos-Lara et al. 2012). Results need to be revised at the end of the study to confirm what the actual catch rates per casita were achieved, and analyse its effects on fishing effort, as well as addressing the environmental impact (Bellchambers et al. 2014).

This project intends to trade-off fishing effort on the large reproductive adults that dwell in coral reef habitats in the southern areas of the bank for fishing effort of sub adults and young adult lobsters harvested from casitas. This trade-off will have to occur gradually once fishers recognize the benefits of a campo system which is inherited by the families as a territorial right over the ocean floor (Gardner et al. 2013), as most are of older ages, prompt to retire with little capital gains and their fishing efficiency in the reefs is progressively reduced.

Market incentives and conservation projects can leverage this initiative as evidenced with the live lobster catching project (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009), as currently almost all of the members of the three fishing cooperatives that operate in BC have abandoned the use of the gaff and now use lobster snares simply because of the surplus

difference in price and quality has allowed for a 30% gain in price and three times increase in volume as lobster heads are no longer discarded. It is expected that all legal lobsters harvested from casitas will be sold live/whole, and will attain the preferred size range for commercial purposes, as the average adult lobsters in BC are occasionally too large for the national tourism standard, although very much appreciated by the Asian market when exported.

If the general principles of SK fisheries are applied (Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013), this initiative in BC could represent a unique exemplary model for assessing management changes in favour of *P. argus* fisheries, and a great opportunity to study the effects of an increased artificial refuge availability in an oceanic atoll where casitas have never been used for commercial purposes (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007). If an appropriate monitoring protocol is implemented for stock evaluation and environmental impact (Bellchambers et al. 2009, de Lestang et al. 2012), following a risk assessment framework (Fletcher 2005, Bellchambers et al. 2014), then knowledge produced as a consequence of this initiative could set the basis to provide a better understanding of the long term dynamics of spiny lobster fisheries where casitas are used (Briones-Fourzán & Lozano-Álvarez 2013), and hopefully provide evidence for recommendations to improve the livelihoods of the artisanal fishers in BC, the MBRS and the wider Caribbean.

As previously mentioned, the wooden casitas which were installed between 2011 and 2013 were destroyed by the effects of Hurricanes Rina and Ernesto (Ley-Cooper 2013). For this reason the previous study was suspended during the development of this thesis, but is yet to be completed in the near future with a casita design made of cement replicating those of SK (see section 1.6.4.1.1), as environmental authorities have acknowledged the benefits of using cement instead of wood. To this date no relevant statistical analysis of the data has been made possible, but it is expected that this chapter will provide enough information to help stakeholders define future management plans for implementation of casitas in the lobster fishery in BC.

As in Ley-Cooper et al. (2011), the implementation of casitas in BC is confirmed as a recommendation emitted by this study, as it is perceived as an opportunity for improving management policies and fishing practices, but only if the extensive deployment is properly monitored and controlled (Lozano-Álvarez 1995). If implementation is successful, fishers

will eventually acknowledge that it is more profitable in the long term to abandon the reefs, not catch large adults, and create for themselves an inheritable capital of territorial based rights (Gardner et al. 2013), which will contribute to their personal income for the future, as well as to the sustainability of this important species (Briones-Fourzán & Lozano-Álvarez 2013). This could be supported by new commercial strategies for adding value such as the MSC (Agnew et al. 2013) and Chakay (Ley-Cooper 2010) ecolabelling initiatives, in order to maximize socioeconomic benefits without increasing fishing effort, which in turn could improve local governance and sustainability within a community-based capacity-building framework (Ley-Cooper 2010, Jain & Garderet 2011, Velez 2014).

5 CHAPTER 5 Estimates of exploitation rates of the spiny lobster fishery for *Panulirus argus* from tagging within the Bahía Espiritu Santo ‘Sian Ka’an’ Biosphere Reserve, Mexican Caribbean

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5.1 Introduction

The *P. argus* lobster is widely distributed from the southern USA to Brazil and throughout the Caribbean (Butler et al. 2008). This species is the most valuable resource fished within the Mexican Caribbean, but there is still a lack of knowledge regarding the basic mechanisms and processes that determine the dynamics of the local populations, which are part of the Caribbean’s meta-population. Historically, spiny lobster fisheries have supported important commercial fisheries along the Caribbean, but increased fishing pressure has reduced lobster abundance, and currently most fisheries are being depleted (Ehrhardt et al. 2010b).

This study was based in Bahía Espiritu Santo, which is located on the central coast of the State of Quintana Roo, in the Mexican Caribbean (Figure 5-1). It is a shallow bay with an area of approximately 300 km² (Sosa-Cordero et al. 1999) with very similar habitat characteristics and oceanographic conditions to Bahía de la Ascensión (Lozano-Álvarez & Negrete-Soto 1991, Sosa-Cordero et al. 1998) which is to the north. Bahía de la Ascensión has been more thoroughly studied (see review by Briones-Fourzán et al. 2000, Sosa-Cordero et al. 2008). Both bays are within the Sian Ka’an Biosphere Reserve (SK), which is a protected area where the fishery is currently co-managed by federal government authorities such as the National Commission for Protected Areas (CONANP) and the National Commission for Fisheries and Aquaculture (CONAPESCA).

In Bahía Espiritu Santo, as in its neighbouring Bahía de la Ascensión (north), the community-based fisheries are organized into cooperatives, and the lobster fishery is based on a ‘casita/campo’ system. Casitas are large artificial shelters that can hold the full size range of lobsters. Casitas are made of cement, with a structural frame of approximately 1.8 x 1.2 m, raised about 10–15 cm above the bottom by two slabs along the longer sides. One or two shorter sides are fully open, allowing lobsters to freely enter and exit the shelter.

Ownership of casitas within these bays are subject to an organizational scheme, which consists of partitioning the fishing areas into parcels (“campos”) allotted to individual fishers, which vary in size from areas of 3 km² to 20 km². A fisherman does not own the campo (as ownership of any sea areas is forbidden by law), but he is free to deploy casitas within it, and hence he owns the casitas and manages his campo in a semi-ownership arrangement (Lozano-Álvarez *et al.* 1991, Briones-Fourzán *et al.* 2000, Defeo and Castilla 2005, Sosa-Cordero *et al.* 2008). The fishers collect from their campos using small boats (7 m long, 60 HP motor) and some GPS devices, and extract lobsters from casitas by skin diving, exclusively using hand nets or snares (López & Consejo 1986, Lozano-Álvarez *et al.* 1989, Lozano-Álvarez *et al.* 1993, Sosa-Cordero *et al.* 1998). Skin diving limits fishing to depths shallower than 15-20 m, (Lozano-Álvarez *et al.* 1991b, Sosa-Cordero 2003, Ley-Cooper 2006). Both the cooperatives licence and fisher’s individual permits are renewed annually, and cooperatives must comply with the federal fishing regulations: a closed season from March to June, a minimum capture size of 135 mm tail length (~74.5 mm carapace length, CL) (Lozano-Alvarez *et al.* 1991b) and a prohibition on the capture of ovigerous females, as well as specific park management rules, such as no-take zones. Internal regulations of the cooperatives forbid the use of SCUBA or hookah-diving, the use of lobster traps, and fishing in someone else’s campo. Historically the semi-ownership of the campos has allowed self-regulation and provided an efficient management arrangement for these fisheries.

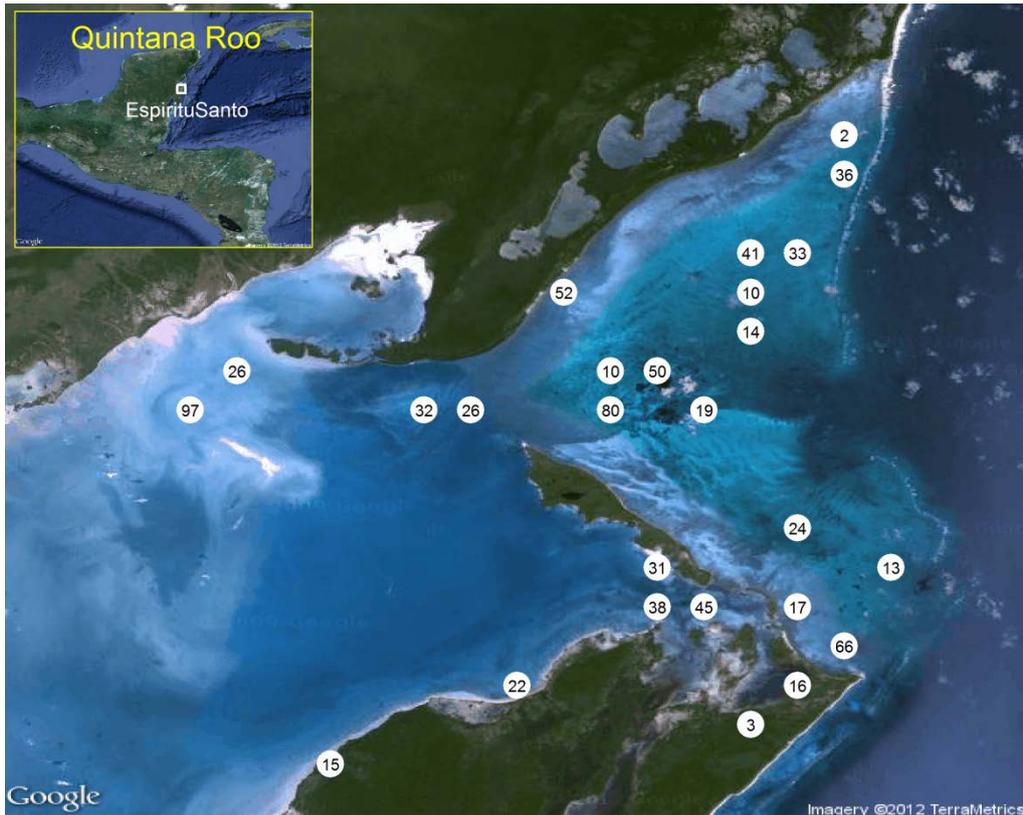


Figure 5-1: Map of Bahía Espíritu Santo South of “Sian Ka’an” Biosphere Reserve Mexican Caribbean. The locations and numbers of lobsters tagged are represented by the numbers in the white circles. The small map insert shows the location of the bay within the state of Quintana Roo.

Exclusive concession rights have been historically granted to three main fishing cooperatives that have managed to maintain the total landings relatively stable in the last two decades (Sosa-Cordero et al. 2008). The age structure of lobsters landed showed a reduced adult mortality, since the catch consists mainly of sub-adult lobsters that inhabit the shallow fishing areas within the bays (Briones-Fourzán et al. 2000), whereas most of the adult lobsters inhabit deeper areas beyond the bays which are not fished (Lozano-Álvarez et al. 1993).

Despite the economic importance of the lobster fishery for the local communities, limited information exists on the lobster population dynamics and exploitation rates of lobsters in Bahía Espíritu Santo (Sosa-Cordero et al. 1999). In the present study, we implemented a mark and recapture programme to assess fishing and natural mortality of adults and sub-adult *P. argus* lobsters inhabiting this bay.

5.2 Methods

5.2.1 Pilot study: Examining Lobster Tag loss

Panulirus argus lobsters (> 74 mm CL) were collected at the study site of Bahía del Espíritu Santo, with hand nets. Lobsters were kept in sea cages for a few days and then transported to the Reef Systems Unit of the National Autonomous University of Mexico at Puerto Morelos. There, lobsters were distributed among three circular fibreglass tanks (3 m in diameter and 0.9 m in height), covered with a dark mesh netting for shading, and supplied with a continuous flow-through seawater system that maintained water temperature and salinity. Each tank contained one or two relatively small casitas to provide shelter for the lobsters.

Other than being fed frozen molluscs and shrimp every three days, the lobsters remained undisturbed for a 10 day acclimatization period. After this period, lobsters were measured (CL, from between the rostral horns to the posterior edge of the cephalothorax) using Vernier callipers (± 0.1 mm) and sexed based on dimorphic characters. Lobsters were tagged with plastic T-bar anchor tags of 50 mm in length (Hallprint, Australia) inserted into the tail extensor muscle between the posterior edge of the carapace and the first abdominal segment using a tag applicator. The applicator needle was sterilized in 100% ethanol before each and subsequent tagging. 26 and 32 lobsters were tagged in two separate tagging trials. The first trial lasted for 135 days, and the second trial lasted for 195 days. Throughout these periods, the tanks were examined daily for dead lobsters and loose tags. Every 2–3 weeks the lobsters were re-measured and examined daily for the presence and condition of their tags. Although these operations may have disturbed lobsters and/or caused tag shedding, tags that were lost were usually recovered on dates not related with those in which these operations were performed.

The lobster tag-recapture model (see below) runs on a monthly timescale and requires a single average lobster tag-loss proportion in each time-step. Therefore, to obtain a monthly average tag loss, the proportion of tagged lobsters in the aquaria each day was averaged on 30 day periods (Figure 5-2). The average monthly proportion of tagged lobsters was then described by an exponential decay equation for input into the tag-recapture model (Figure 5-2).

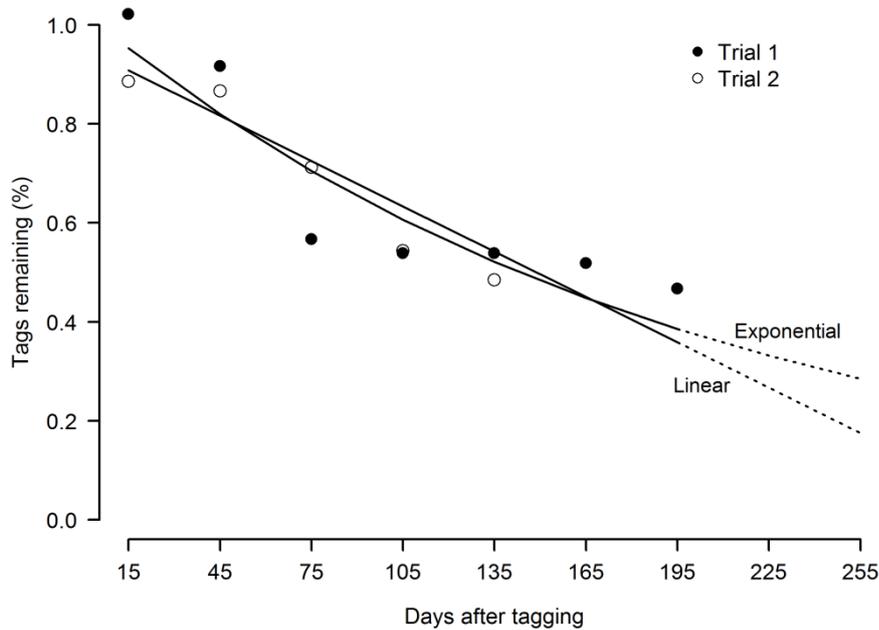


Figure 5-2 Proportion of lobster retaining tags over time derived from experimental aquaria tanks using T-bar Hall print tags in two independent trials.

We did not differentiate between tag-shedding, natural mortality resulting from the tags being lost, nor tag-induced mortality because for the purpose of the model, the important factor was the proportion of lobsters that remained tagged after a specified time.

5.2.1.1.1 Brownie Model

5.2.1.1.2 Lobster Tagging Protocol

Lobsters were captured from “casitas” across the bay and lagoon areas of Bahía Espíritu Santo (1–7 m in depth) by using hand nets and carried back to the boat for tagging. Lobsters were tagged in the same manner as the tag-loss trials. The tag number, tagging date, location, lobsters sex and carapace length were recorded for each tagged lobster and then the lobster was immediately returned to the same casita. Tagging was conducted in June (during the closed season) and in July, September and October 2010 (during the fishing season). Only lobsters ≥ 44.0 mm CL were tagged to reduce incidental mortality (Lozano-Álvarez et al. 1991b), with the majority of tagged lobsters being >60 mm CL.

5.2.1.1.3 Estimating the reporting rate

The tagging program was advertised widely and included a reward system to encourage lobster tag returns. Throughout the July 2010 to February 2011 fishing season, two technicians were in frequent contact with fishers and administrators of the two cooperatives that fish at Bahía Espíritu Santo. Fishers were interviewed weekly to discuss the progress of the study and to prompt them to continue to report tagged lobsters. During these interviews, the fishers were asked whether they had caught but not reported tagged lobsters and, if so, to at least provide information on the tag numbers. Because of the high level of interaction between researchers and fishers the tag-reporting rate was considered to be 100%.

5.2.1.1.4 Mortality estimates

Instantaneous rates of fishing and other mortality for *Panulirus argus* in Bahía Espíritu Santo were estimated using a Brownie model (Brownie et al. 1985) that was modified to allow for the incomplete mixing of tagged lobsters during the first period of recapture and to incorporate fishing effort data (Hoenig et al. 1998) (Table 5-1). These modified attributes of the Brownie model were important as they accounted for the behaviour of *P. argus* after tagging. Since previous tagging work in Bahía de Ascensión (Lozano-Álvarez et al. 1991b) was unable to determine whether natural mortality or emigration were the cause of tag-loss, our model assumes that mortality other than that due to fishing is a combination of natural mortality and emigration.

Because tagged lobsters were returned to the same casita from which they were captured, initially all tagged lobsters were heterogeneously distributed throughout the bay. However previous studies showed that lobsters actively move between casitas (Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2001a), and that one month after tagging the distribution of tagged lobsters throughout the bay could be considered more homogeneous (Lozano-Álvarez et al. 2003). The re-parameterisation of the model accounts for this initial non-mixing of tagged and untagged lobsters by applying a specific non-mixed estimate of catchability (\hat{q}_j) for all lobsters recaptured with a liberty time of less than two months.

In the modified model, other forms of mortality (e.g. natural mortality, emigration) were assumed to remain constant over the entire fishing season, whereas catchability (q) was allowed to vary between months. Estimates of the instantaneous rate of fishing mortality (F) were determined as $F = qE$. Catch and effort data were collected from the fishing

cooperatives landing logbooks and verified against data from tax declaration forms. All catches were converted to whole weights (kg) using a conversion factor based on the relationship between tail weight and whole weight previously reported by Lozano et al. (1991b). The unit of effort used was fishing trip adjusted to a monthly proportion of the entire season's fishing effort.

Table 5-1: Expected number of tag recoveries when additional lobsters are tagged and added to the population at the start of each fishing month. Symbols are as follows: N_j number of tagged lobsters released in month j ; Φ probability of retaining a tag; tag reporting rate; q_j catchability of the lobsters in month j ; incomplete mixed catchability of the lobsters in month j ; E_j proportion of seasons total effort in month j ; M instantaneous rate of natural mortality.

| Expected recoveries in each month | | | |
|-----------------------------------|---|--|---|
| Month | 1 | 2 | 3 |
| 1 | $\frac{N_1 \phi \lambda \hat{q}_1 E_1}{\hat{q}_1 E_1 + M} (1 - e^{-\hat{q}_1 E_1 - M})$ | $\frac{N_1 \phi \lambda q_2 E_2}{q_2 E_2 + M} (1 - e^{-q_2 E_2 - M}) e^{-\hat{q}_1 E_1 - M}$ | $\frac{N_1 \phi \lambda q_3 E_3}{q_3 E_3 + M} (1 - e^{-q_3 E_3 - M}) e^{-\hat{q}_1 E_1 - q_2 E_2 - 2M}$ |
| 2 | | $\frac{N_2 \phi \lambda \hat{q}_2 E_2}{\hat{q}_2 E_2 + M} (1 - e^{-\hat{q}_2 E_2 - M})$ | $\frac{N_2 \phi \lambda q_3 E_3}{q_3 E_3 + M} (1 - e^{-q_3 E_3 - M}) e^{-\hat{q}_2 E_2 - M}$ |
| 3 | | | $\frac{N_3 \phi \lambda \hat{q}_3 E_3}{\hat{q}_3 E_3 + M} (1 - e^{-\hat{q}_3 E_3 - M})$ |

The lobster tag-recovery data were analysed using a Brownie model (Brownie et al. 1985) as modified by (Hoenig et al. 1998) and described in this paper. The model was constructed in R (R Development Core Team 2010) with its Log-Likelihood maximised using a Nelder-Mead method in the optimum routine (Nelder & Mead 1965, Nash 1990)

5.3 Results

5.3.1 Examining lobster tag loss and tag reporting rates

In both trials, the rate of average monthly lobster tag loss for each trial was initially rapid before progressively lessening until the end of the experiments, 4.5 and 6.5 months later respectively (Figure 5-2). The relationship between the number of months after release (time at liberty) and the proportion of lobsters retaining tags was better described by an exponential

decay (Akaike's An Information Criterion (AIC) = -23.2, $r^2 = 0.86$) rather than by a linear relationship (AIC = -18.9, $r^2 = 0.8$) (Sakamoto et al. 1986). The exponential decay relationship describing the monthly proportion of tags remaining on lobsters was equal to $TL = 0.953 * e^{(-0.151*L)}$, where TL is the proportion of lobsters still tagged and L is the number of months after release.

5.3.2 Brownie model

5.3.2.1.1 Tag recaptures

During the first two months of the fishing season, the fishers actively contacted research staff and submitted all requested information. However many became less interested from about the third month of the season, and had to be prompted to provide the data. The cooperatives retained all information and passed it onto researchers every month. Fishers had three opportunities to search for tags before handing lobsters to third parties: a) when catching them by free diving, b) when taking them from personal cages to where they are weighed, and c) when weighed at the cooperatives headquarters for sale.

Table 5-2 Data represented in the input form for the Brownie model with rows and columns representing tag release and recapture respectively. NSA represents the tags Never Seen Again.

| Tag Recaptures by Month | | | | | | | | | | | |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------|-----|
| Month | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Released | NSA |
| Jun | 0 | 105 | 35 | 29 | 9 | 2 | 5 | 0 | 0 | 568 | 383 |
| Jul | | 27 | 15 | 14 | 5 | 3 | 1 | 1 | 2 | 174 | 106 |
| Aug | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sep | | | | 2 | 1 | 0 | 0 | 0 | 0 | 3 | 0 |
| Oct | | | | | 0 | 8 | 2 | 2 | 0 | 41 | 29 |

In total, 786 lobsters were tagged throughout the Bay of Bahía Espíritu Santo, of which 268 (34%) were recaptured, with most recaptures occurring at the beginning of the

fishing season from July through September (Table 5-2). Many lobsters that were recaptured in July and August had been released near the point of recapture (see Figure 5-1), whereas many lobsters that were recaptured from October to December were found near the coral reef areas located east of the bay. These lobsters travelled distances ranging from 1.3 to 18.2 km within the bay. However, five lobsters that were originally tagged in Bahía de la Ascensión on April 2010 as part of a separate study (Lozano-Álvarez et al. unpublished data) were recaptured in Bahía Espíritu Santo. These lobsters had travelled an average of 43.5 km in a southward direction.

5.3.2.1.2 Fishery Catch and Effort statistics

In Bahía Espíritu Santo, the monthly catch (whole weight) and effort (fishing trips) showed slightly different trends over the course of the fishing season (Figure 5-3). Effort decreased progressively from its maximum value in the first month of the fishing season (July 2010) to its minimum level by December 2010 and then remained relatively constant through to the end of the fishing season (February 2011) (Figure 5-3). Catch declined after the first month, and then increased over the next three months before decreasing again to stabilize at a low level (Figure 5-3). The catch per unit of effort (CPUE) began in July near maximum levels at 50 kg/trip before decreasing to the lowest level of 28 kg/trip the following month (August) (Figure 5-3). Catch rates subsequently improved over the next three months to a maximum catch rate of 52 kg/trip in November before declining slightly to between 35 and 46 kg/trip from December to February 2011 (Figure 5-3).

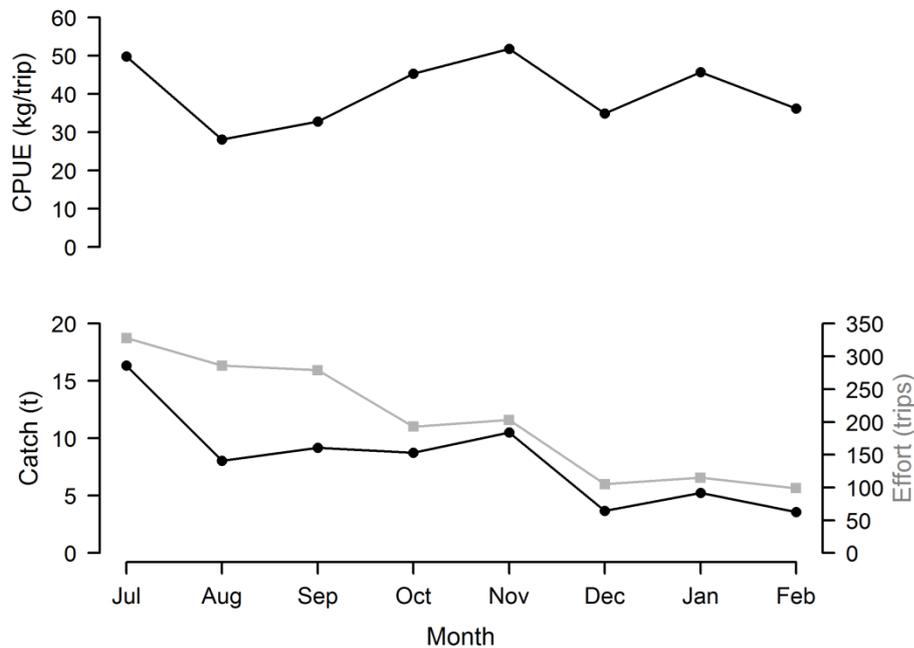


Figure 5-3: Catch per unit of effort (CPUE -Kg/trip) (top figure), Catch (t) [black circles] (bottom figure) and Effort (trips) [grey squares] (bottom figure), in each month of the fishing season from July 2010 to February 2011.

5.3.2.1.3 Lobster Tag recaptures and estimates of Exploitation rate

A 34% recapture rate allowed for a good estimation of the fishing parameters and criteria for outputs of the model. Tagged lobsters that were released in the four discrete pulses (June, July, September and October) were recaptured in large proportions, i.e. 33, 39, 100 and 29 %, respectively. The Brownie model estimated the monthly levels of exploitation required to reproduce similar proportions of tag-recaptures and the numbers of tags never seen again (NSA) (i.e. never recaptured) (Table 5-2, Figure 5-4). The numbers of NSA tags were relatively high for the first, second and fourth tag release pulses since large numbers of lobsters were released in these pulses and only a fraction of lobsters were recaptured (Table 5-2, Figure 5-4).

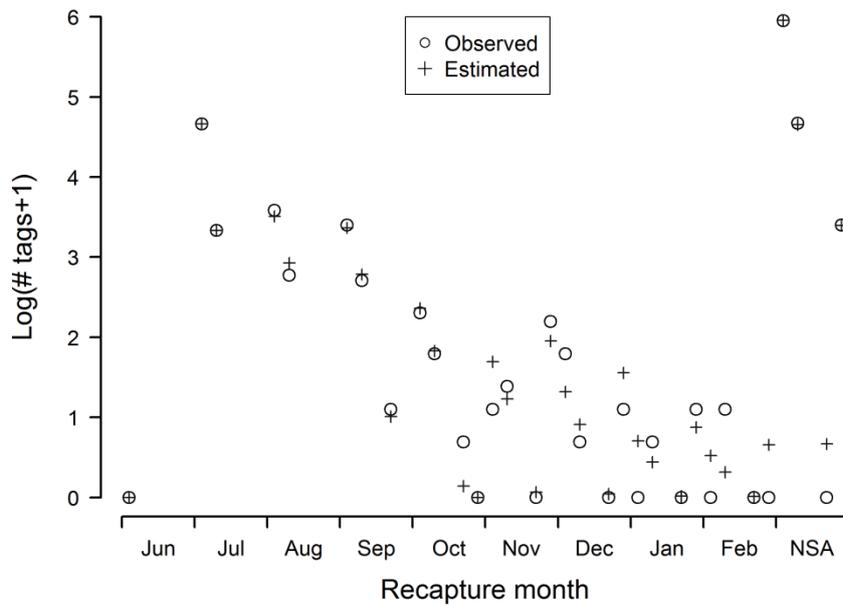


Figure 5-4 Observed (circles) and estimated (crosses) tag recoveries in each month of the fishing season from July to February with all non-recovered tags represented on the right hand side of the plot (Never Seen Again: NSA).

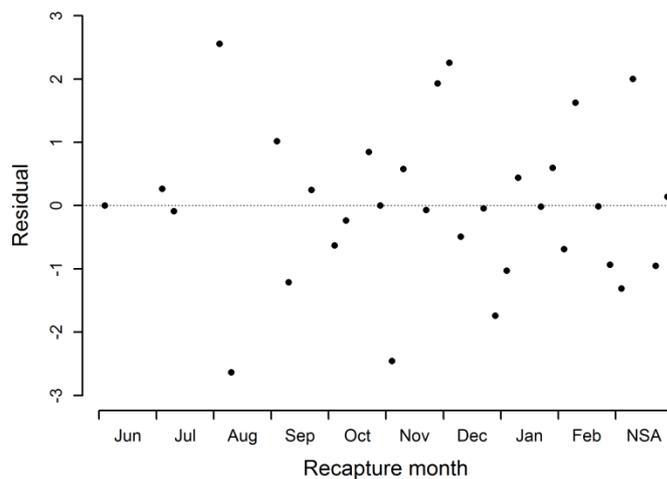


Figure 5-5: Residuals from the Brownie model (observed - estimated).

A residual plot of the model fit to the observed data indicated that the model was able to closely reproduce the pattern of tagged lobster recaptures with the error in the model estimates being evenly distributed (unbiased) between the four tagging/release periods and nine recapture periods (Figure 5-5).

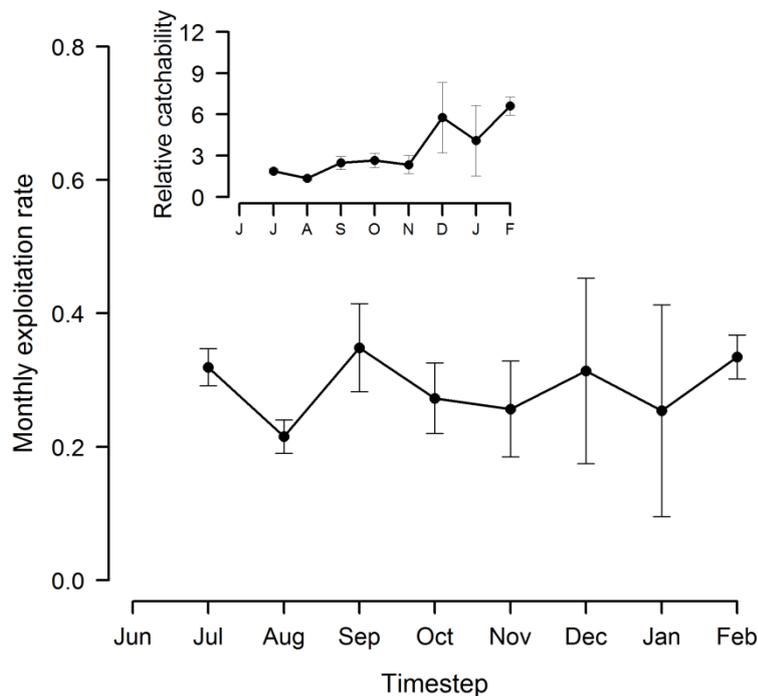


Figure 5-6: Exploitation rate ± 1 standard error and relative catchability ± 1 standard error (small insert) in each month of the fishing season from July 2010 to February 2011.

Model estimates of relative catchability differed dramatically between those representing unmixed (\hat{q}) and mixed catchability for the same time periods (e.g. 0.99 and 6.47 (unmixed) versus 1.89 and 2.47 (mixed) in July through September, respectively). Estimates of relative catchability (q) remained fairly constant between July 2010 and November 2010, with a tight fit of values and their standard errors (see inset in Figure 5-6). Mean catchability (q) increased in the last three months of the fishing season although the confidence intervals for December and January continued to overlap those of earlier months. Estimates of monthly exploitation rates showed a slightly different pattern than those of catchability. Exploitation rates ranged between 0.22 and 0.35 with highly overlapping confidence limits in all months (Figure 5-6). The total exploitation rate (the cumulative sum of monthly exploitation) and average rate of other mortalities estimated by the model were 0.94 and 0.24.

5.4 Discussion

The number of lobsters that we used for estimating tag loss was partially limited by time and space availability. In addition, the potential effects of the behaviour, moulting, and

the size and sex of lobsters on tag shedding have not been explored. Although further studies taking into account these factors may provide more information on the lobsters shedding of tags and lobster tag-induced mortality (Ehrhardt 2008), the data on “tag loss” that we obtained during the tank trials lies within the range obtained in previous studies on other lobster species (Montgomery & Brett 1996, Dubula et al. 2005). Considering that the trend in tag-loss in both trials followed the same pattern after time-step 4 (as shown in Figure 5-2), the equation for tag loss would be valid for the time-steps remaining after the experiment was suspended; therefore, a longer period for field recaptures would be unaffected in the model.

The monthly tag loss obtained from the tank trials indicated that over time there is an exponential-like loss of individuals from a tagged *Panulirus argus* population. For other lobster species, patterns showing an abrupt initial “tag loss” in the first few weeks post-tagging have been attributed to tag-induced mortality (Dubula et al. 2005) and tag shedding (Montgomery & Brett 1996). In our tank experiment, we observed that tag loss in lobsters was also associated with moulting activity and occasionally with cannibalism of lobsters about to moult or recently moulted. The latter behaviour can reflect stress associated with conditions of captivity (Moriyasu et al. 1995). However, tag loss due to these factors could be lower in natural habitats, where lobsters about to moult may isolate themselves.

Non-linear mortality patterns among tagged lobsters that were initially greater and then comparable to the control (untagged lobsters) were reported by (Montgomery & Brett 1996). They concluded that tagging causes only a short-term increase in mortality but is not significant in the long term when compared to the effects of natural mortality. This precedent supports our case in which an exponential decrease in tag loss (as is shown in Figure 5-2) is representative.

Having a continued presence of observers on the field, along with a reward-based, tagged lobster reporting scheme, should be comparable to high-reward tagging studies that have shown it is possible to determine an exploitation rate from the tagged lobster recovery rate (Hoenig et al. 1998). The increase in likelihood of fishers not reporting tags as the months advanced was not a concern in this study as rewards were given. This model used under this scheme is hereby considered an effective mortality estimation tool.

We assumed that it would take approximately two months for newly tagged lobsters to disperse and fully mix with the rest of the population. Consequently, our non-mixing model was developed to account for these differences, because tagged lobsters were

immediately placed under the same casita in which they were found, considering that they exhibit a certain degree of shelter fidelity because of their foraging and gregarious behaviour (Briones-Fourzán et al. 2007).

The model estimated that all other sources of mortality had a rate of 0.24 ± 0.02 (mean \pm SE). This estimate represents all removals of lobsters by factors other than fishing, tag loss or tag induced mortality, such as natural mortality and emigration. As none of the tagged lobsters were recaptured outside of the bay, and very few were recaptured in the outer reef area, it is likely that our estimate is predominately a measure of natural mortality. This estimate is well within the range of other estimates form in *P. argus* in the Mexican Caribbean (Lozano-Álvarez et al. 1991a, Lozano-Álvarez 1994, Arceo et al. 1997, Arce et al. 2001, Sosa-Cordero 2003, Sosa-Cordero et al. 2008) This natural mortality rate, in conjunction with a total annual exploitation rate of 0.94, implies that a large amount of recruitment (growth and/or immigration) must occur within this bay to maintain catch rates throughout the fishing season. Thus suggesting that throughout the 2010-2011 fishing season, all legal-sized lobsters found within the bay and at depths < 20 m (depth limit for free-diving) were fished. It remains to be determined whether lobsters found deeper than 20 m have an effect on the dynamics related to the yearly casita replenishment processes.

In Bahía de la Ascensión, the highest annual CPUE (kg tail weight per boat per day) in the fishery also occurs in July, at the onset of the fishing season, and declines sharply during the rest of the fishing season. This trend has been mainly attributed to the combined effects of natural and fishing mortality (Lozano-Álvarez et al. 1991b). According to (Sosa-Cordero et al. 2008) fishing effort tracks the catch trajectory, an indication that fishers reduce their activities (and hence their costs) when the local lobster resource is scarce. That is, the annual CPUE reflects fishing efficiency rather than resource abundance. This notion may also explain why, in Bahía Espíritu Santo, despite a relatively constant monthly catch from August to November, CPUE values showed an increasing trend during this period (see Fig. 3). In particular, the high levels of CPUE during October and November may be associated with the onset of the “Nortes” (cold fronts arriving from the north), which may increase movements of lobsters into the bay (Lozano-Álvarez et al. 1993) and the potential for casita replenishment. This is also suggested by the recapturing in Bahía Espíritu Santo of five lobsters that were tagged outside of the bay (Lozano-Álvarez et al. unpublished data).

At Bahía Espíritu Santo, the regulations on fishing gear result in a limited access to the deep lobster stock (> 20 m), where reef areas and a high proportion of reproductive adults are found (Lozano-Álvarez et al. 1993). Results from the non-mixing tagging Brownie models analysis presented here, imply that to sustain a 0.94 annual exploitation rate of the population subject to fishing, there must be a constant source for lobster replenishment into the casitas found within this bay.

A fishery with a management scheme based on casita/campo system may well be functioning as an artificial refuge area that increases abundance and population density from several sources, such as larval recruitment, enhanced juvenile survival and growth (Briones-Fourzán et al. 2000) and adult attraction of lobsters migrating inshore and south during the early winter and closed season (Herrnkind 1980).

A trend observed is that as the fishing season advances from July to February, the CPUE does not decrease substantially, yet total landings do so, while fishing mortality (F) remains relatively stable. These results suggest a continuous input of lobster biomass into the casitas that is clearly higher during the closed season, potentially explaining the peak in catch at the beginning of the fishing season (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007). However, as the season advances, lobster availability decreases as indicated by the increase of catchability of tagged lobsters (see Figure 5-6). Periodic and yearly casita replenishment shows the need for assessing the proportion of the lobster stocks dwelling outside the bay (Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998).

An option for dealing with non-mixing models is to increase the number of recaptures and tagged lobster reporting rates or to use a model that assumes the period of non-mixing lasts for less than a year. We have provided a type of model intermediate between the Brownie-like models and exact time of recapture models (Hearn 1986, Hearn et al. 1987) considered to apportion the total recaptures from a cohort to sub-annual two month periods. We have determined an expression for the expected value for each cell of the recovery matrix and raised the expected value to the observed number in the cell, as suggested by (Hoenig et al. 1998). In addition to increasing the precision of the estimates, this type of model enables one to estimate the fishing mortality in the first time step of the study and consider a solid statistical theory captured in the Hoenig et al. (1998) models. More definitive information on emigration and the tagged lobsters reporting rate would be very valuable.

6 CHAPTER 6: An unfished area enhances a spiny lobster (*Panulirus argus*) fishery: Implications for management and conservation within a Biosphere Reserve in the Mexican Caribbean

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6.1 Introduction

Marine Protected Areas- (MPA's) are often defined as no take zones where fishing is prohibited. As part of the conservation efforts to sustain exploited species such as lobsters, MPA's are designed to preserve important habitats that serve as shelter, foraging grounds or movement corridors, as well as protecting the breeding stocks and increasing the fishery yield of the target species (Acosta, 1999; Goñi, *et al* 2010). In Biosphere Reserves like Sian Ka'an (SK-BR see map rectangular insert Fig. 1), where fishing is allowed but access is restricted and operations only occur within areas of less than 20 m depth (Ley-Cooper, *et al* 2013; MRAG-Americas, 2012), management initiatives are also expected to replenish stocks by increasing biomass and abundance. However few empirical studies have demonstrated whether these management initiatives optimize population viability, and how they may affect benthic dispersal dynamics of the *P. argus* (Acosta 1999).

Assigning no take areas where fishing is totally banned is being promoted as a conservation strategy for heavily exploited species such as *P. argus*, although there is generally only limited evidence that movements of adult individuals from unfished areas replenish the populations in areas subject to fishing ('spillover effect') (Russ, *et al* 1996; Goñi, *et al* 2010). This is also the case in the SK-BR where un-fished offshore areas deeper than 20 m are unofficially conceived as no take areas of the MPA. These areas are especially valuable for sustainability since they are predominantly populated by mature-sized lobsters (Ley-Cooper *et al.*, 2013; Lozano-Álvarez *et al.*, 1993). Understanding both recruitment and lobster movement patterns from the deep unfished area into the fishery can help evaluate the Biosphere Reserve's potential to meet management performance standards, by providing information about habitat use, home range, migrations, retention times/spillover, and location of spawning grounds (Goñi *et al.*, 2006; Bertelsen, 2013). Given the complexity of the post

larval settlement and recruitment patterns of *P. argus* (Briones-Fourzán et al. 2008), the only tangible fishery benefit that can be demonstrated in favour of the deep unfished areas is the recruitment of adults which replenish the shallow fishing grounds (< 20 m) enhancing fishing yields (Russ & Alcala 1996; Bevacqua *et al.* 2010). This is usually examined via tagging experiments (Frusher & Hoenig, 2003; Goñi *et al.*, 2010; Bertelsen 2013).

Spiny lobster *Panulirus argus* is the most valued single species fished in the Caribbean and the main economic source for families living in the Sian Ka'an Biosphere Reserve, Mexico (SK-BR). The marine segment of the SK-BR is an MPA, where restricted fishing for lobsters is permitted to three cooperatives with exclusive concession rights within both existing bays - Bahía de la Ascensión and North and Bahía Espíritu Santo-South (Fig. 1) Ley-Cooper et al. (2013). Fishing operations are confined to the shallow areas (<20 m) west from the barrier reef due to restrictions in fishing gear and regulations, since only free diving is allowed and the use of any sort of alternate air source or deep trap is banned (Sosa-Cordero et al. 1999, Ley-Cooper et al. 2013). As a result, only the portion of the whole lobster stock lying within shallow waters is exploited (area I, Fig 1) and the deep offshore area (>20 m) is effectively a no take zone which is unfished (area II, Fig 1). This limitation is a main criterion for the sustainable management of this fishery. However the MSC certification process identified the multiple sources of recruitment variation and movement of adult lobsters to and from the deep areas as one of the main sources of uncertainty in assessing the stock status (MRAG-Americas 2012).

Panulirus argus displays movement behaviours throughout its life cycle for many purposes, including relocating to more appropriate habitat and foraging for food and reproduction (Acosta 1999, Briones-Fourzán et al. 2003, Ríos-Lara et al. 2007). After settlement within shallow vegetated areas juveniles attain a transitional size (typically >15-20 mm carapace length CL) at which they begin to seek shelters (rock crevices, holes and ledges; undercut coral heads and sponges). Emigration out to deeper reef areas for reproductive purposes begins to occur in pre-adult lobsters (size \approx 75 mm CL).

How the physical characteristics of the deep segment (>20 m) of the SKBR MPA interacts to support a viable population of *P. argus* in the shallows has been the focus of much discussion, but few empirical studies have investigated the mechanisms which affect adult dispersal, distribution or abundance - information important for designing protected areas (Acosta 1999, Bertelsen 2013). Little is known about the population dynamics of lobsters that dwell in the deep platform and the offshore areas (\geq 20 m) of the SK-BR

(Lozano-Álvarez et al. 1993, Ley-Cooper et al. 2013). It is possible that some adult lobsters from the deep water stock may migrate into the shallow areas as a result of dispersal movements, for reasons such as: returning after spawning (Bevacqua et al. 2010, Bertelsen 2013); seasonal behavioural changes (Herrnkind 1980, García et al. 1991, González-Cano 1991, Lozano-Álvarez et al. 1993) or in search of food and shelter (Ríos-Lara et al. 2007). To date, the proportion of lobsters that might move inshore from deep areas has not been estimated and the assumption that the adult stock is fully protected in deeper waters should be re-examined for this BR.

More robust stock assessment and the establishment of biological reference points have been suggested as means to improve the management and evaluation of the lobster fisheries in SKBR, and now form a condition for the on-going sustainability certification granted by the Marine Stewardship Council (MSC) (MRAG-Americas 2012). In this fishery, exploitation rates are high within the shallow bays (depths <20 m, area I), and it has been suggested that, in order to sustain such catch rates lobsters, recruitment to this fishery must be frequently replenished by growth of juveniles and/or by an input of lobsters moving in from unfished areas such as those found offshore in deeper waters (>20 m) (González-Cano 1991, Lozano-Álvarez et al. 1991b, Lozano-Álvarez et al. 1993, Briones-Fourzán et al. 2007, Ley-Cooper et al. 2013).

This paper addresses the question of how the present management regulations, which constrain fishing to depths less than 20 m, may affect benthic dispersal dynamics of the *P. argus*, and their catch rates within the Sian Ka'an Biosphere Reserve. We used a multi-state mark recapture model to test the hypothesis that an autumn season migration takes place, with a proportion of lobsters moving from the offshore (>20 m) unfished areas of the MPA into to the shallow areas which are fished. The impact this has on fishing yields is examined and discussed.

6.2 Materials and Methods

6.2.1 Study area

The study was conducted in the Mexican Caribbean, in the central segment of the coast of Quintana Roo/Yucatan Peninsula within the SKBR/MPA. Here, the continental shelf is narrow, not exceeding four km from the coast and ending at depths averaging 50 to 60 m, after which depths rapidly reach >400 m (Lozano-Álvarez et al. (1991a). The SK-BR encompasses two large marine embayment's named Bahía del Espíritu Santo (south) and

Bahía de la Ascensión (north) (Fig.1). Bahía del Espíritu Santo is a large and shallow bay ranging in depths from 1-20 m, with an area of approximately 300 km² (Sosa-Cordero et al. 1999). Within this bay there is a limited access fishery exclusively exploited by two cooperatives, and co-managed by environmental and fishery federal government authorities (Sosa-Cordero *et al*, 2008).

For the purposes of our study, the bay was divided into two areas (Figure 6-1): area I, the commercially exploited shallow bay (<20 m) to the west and area II, the un-exploited offshore deeper area (>20 m) to the east. In practice, area II is a “no take” zone within this BR, since diving with the use of alternative air sources (e.g. SCUBA) is prohibited, although lobsters (*P. argus*) are naturally distributed in both areas (Phillips 2006).

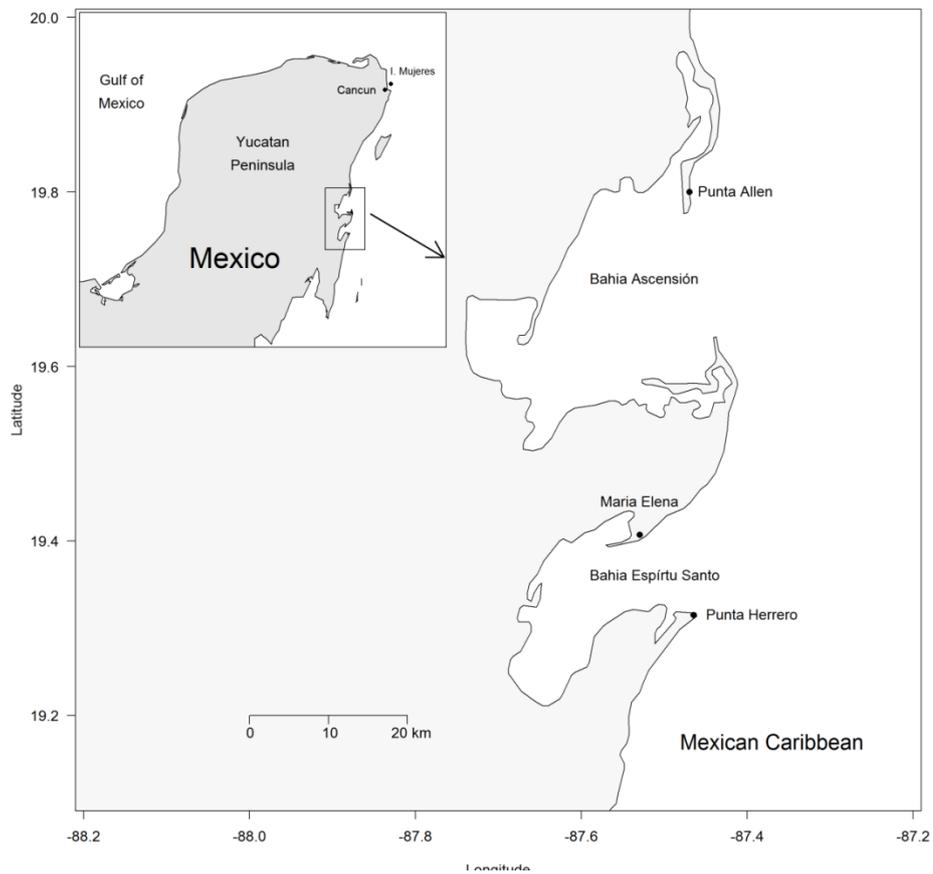


Figure 6-1 Map showing Mexico and the study area called Bahía del Espíritu Santo, which is the southern bay of the Sian Ka'an Biosphere Reserve (the reserve area is identified by the rectangle on the map insert). Bahía de la Ascensión is neighbouring to north, and the Caribbean sea to the east of the Yucatan Peninsula. Areas are marked as “I” the fished shallow bay (<20 m deep), and “II” the unfished offshore area (>20 m deep) respectively.

6.2.2 Description of the fishery and local stock

The lobster fishery is based on concessions to two cooperatives which fish using a “Casita/Campo” system. Casitas are large artificial shelters that can harbour the full size range of lobsters, and are allotted to individual fisher families associated to the cooperative. The bay and fishing areas are divided into parcels called Campos, and are hence owned by the “family” who manage them in a semi-ownership arrangement (Lozano-Álvarez *et al.*, 1991a; Lozano-Álvarez *et al.*, 1991b; Briones-Fourzán *et al.*, 2000; Sosa-Cordero *et al.* 2008). Permits are renewed annually and cooperatives must comply with the federal fishing regulations, which include a closed season from March 1 to June 30; a minimum tail size of 13.5 cm (~74.5 mm, CL; Lozano-Álvarez *et al.* 1991a; Lozano-Álvarez *et al.* 1991b); and prohibition of capturing egg bearing females.

Lobsters are caught mainly in the bays within the fringing reefs using small boats and by skin diving to a maximum depth of 20 m (Ley-Cooper *et al.* 2013). For the purpose of this study we refer to the “local” stock as the proportion of the population found within the bay, including the adjacent water areas found beyond the reef and to the east of Bahía del Espíritu Santo (depths ≤ 100 m) (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán *et al.* 2007).

6.2.3 Lobster tagging and recapture:

Tagging: A total of 379 lobsters, (56 in August and 323 in September, 243 females and 136 males), were tagged and released where they had been caught, in water depths which ranged between >20 m and < 40 m, in area II (Fig.1), during the first five days of each month in 2011. All lobsters were caught using hand nets or snares while fished using SCUBA, and were tagged with T-Bar tags (“Hallprint”, Australia) in their ventral abdomen region as described by (Ley-Cooper *et al.* 2013). The size range of tagged lobsters was 70.1 to 140.5 mm CL. Fishing location, sex, and size (CL), were recorded for each lobster.

Recaptures: Recaptures were obtained from both licenced fishing boats and the cooperative depots during the fishing seasons 2011/2012 and 2012/2013. Research observers went on-board boats for 10 days during every month of the fishing season. Additionally information on tag reporting in log books was obtained at reception points.

6.2.4 The Multi-State Tag Recapture Model:

In order to estimate the monthly movement rates of tagged lobsters from an unfished area (area-II) to a fished area (area-I) during each month of the fishing season following the tag releases (i.e. August 2011 – January 2012), a multi-state tag-recapture model (MSTR) was developed based on a model framework described by Hilborn (1990). The model, built in “R” (R Development Core Team 2012), encompassed only the first fishing season following release (2011/12) since this period covered the majority of tag returns. Returns in the 2012/13 season were so few they provided too little information for the MSTR model to determine movement rates with any degree of confidence.

A model was custom-built for this study because previously developed models, such as those found in packages like ‘MARK’ (White & Burnham 1999), required tagging and recaptures to occur in both areas in its multi-state design. In our study, lobsters were only tagged and released in the unfished deep area >20 m (area II) and recaptured only in the shallow fished area < 20 m (area I). The MSTR model incorporated fishing and natural mortality, reporting rate, and tag loss. It differed slightly from that described by (Hilborn 1990), in that it also included natural mortality, all mortality was treated as instantaneous, and a four- rather than a three-dimensional array was used to track lobsters.

The model consisted of four main components, which combined allowed us to determine the likelihood of recapturing a tagged lobster in the shallow fished area. These components represented the processes of tag-release, migration, mortality (fishing/natural/tag-loss) and likelihood of recoveries. The model employed a monthly time-step (August - January) and considered the numbers of tagged lobsters at liberty and recaptured in each time interval starting in the calendar month when lobsters were first released (August 2011) and terminating at the calendar month when the last recaptured lobster of that fishing season was recorded (January 2012). The model grouped lobsters into two areas: I) the fished shallow-waters (<20 m), and II) the offshore unfished deeper-waters (>20 m). The model contained a series of assumptions:

1. Tag loss would occur at a rate previously determined from aquaria studies (Ley-Cooper *et al.*, 2013). The exponential decay relationship describing the monthly proportion of tags retained was equal to: $TL = 0.953 * e^{(-0.151 * L)}$, where TL is the proportion of lobsters still tagged and L is the number of months after release. This rate of tag loss lies within the ranges obtained by other lobster studies (Forcucci *et al.*

1994, Montgomery & Brett 1996, Sharp et al. 2000, Dubula et al. 2005, Ehrhardt 2008)

2. Commercial fishing effort was homogenous across the entire fishery.
3. Each lobster within the model had the same probability of being captured.
4. During the study tagged lobsters will not migrate twice, i.e. will not enter the fishery and then leave.
5. Natural mortality was previously determined within the bay in a study carried out during the previous fishing season (Ley-Cooper *et al.*, 2013), and is assumed to be constant over time and model area.

6.2.5 Analysis of tag data

Data from tagged lobsters were recorded within the MSTR model, using a four-dimensional array that recorded their expected abundance against: a) their initial release location, b) the month they were released, c) their recapture location and d) the month of recapture. At the start of each time-step, tagged lobsters were recruited into the model using the equation:

$$N_{r,m,a,t} = T_{r,m} + N_{r,m,a,t-1}$$

where $N_{r,m,a,t}$ represents the number of tagged lobsters from the release area (r) (area II), released in month m and currently residing in area a (area I), during the model time-step t , and $T_{r,m}$ represents the number of tagged lobsters initially released: m and t range from May to January ($n=11$), whilst r and a represent lobsters moving from deep to shallow ($n=2$).

Migration

Following the recruitment of tagged lobsters, the MSTR model estimated a time-step specific proportion of tagged lobsters (P_t) that were uni-directionally migrating from the unfished area to the fished area using the equations:

$$N_{r,m,1,t} = N_{r,m,2,t} * P_t,$$

$$N_{r,m,2,t} = N_{r,m,2,t} * (1 - P_t).$$

6.2.6 Estimates of mortality, recoveries and tag loss

Estimates of F and M were based on previous estimates determined for this same fishery in the previous fishing season 2010/11 and were assumed to remain constant across the fishing season (Ley-Cooper et al. 2013). These values were not determined by the MSTR model since no tagging occurred within the fished area (I). Since the average monthly estimate for F had been determined for the previous fishing season at ~ 0.3 (Ley-Cooper et al. 2013), a range of values that encompassed this (e.g. 0.1, 0.15, 0.2, 0.25, 0.4, and 0.5) were utilised to determine how sensitive the model was to the estimate of F . The instantaneous rate of natural mortality (M) of 0.02 month^{-1} used in this study was also taken from the (Ley-Cooper et al. 2013).

The rate of tag loss used in the model (about $14\% \text{ month}^{-1}$) was based on the rate previously reported for *P. argus* in the same fishery (Ley-Cooper et al. 2013), and it represented the expected reduction in the number of tagged lobsters at liberty, due to tag shedding and tag induced mortality. After allowing for the migration of lobsters between areas, 50% of the estimated monthly tag loss was applied to the simulated population of lobsters, both before and after fishing and natural mortality had both been applied. Tag loss was applied to the simulated population of lobsters in the model by using the equation:

$$N_{r,m,a,t} = N_{r,m,a,t}(1 - e^{-2.65}).$$

Interviews with fishers indicated that the tag reporting rate for this study was $\sim 30\%$ less than that of the previous seasons estimate of 100% return rate (Ley-Cooper et al. 2013). This was considered to be due to less direct interaction with the fishers and that tag reporting was becoming less novel. As such a range of tag reporting rates encompassing this estimate (60 – 80%) were trialled in the model to assess its sensitivity to this parameter.

Instantaneous rates of fishing (F) and natural mortality (M) were applied to the population once tagged lobsters had been released, migrated and reduced in magnitude through tag loss. Simulated catches were also affected by a tag reporting rate (λ) which was applied before the lobsters were considered to have been reported to the survey team. The estimated number of recaptured lobsters reported to the survey team and the numbers left in the water were determined using a Baranov catch equation:

$$\hat{R}_{r,m,a,t} = N_{r,m,a,t} * \frac{F_{a,t}}{F_{a,t}+M} * \left(1 - e^{-(F_{a,t}+M)}\right) * \lambda_{a,t},$$

$$N_{r,m,a,t} = N_{r,m,a,t} * e^{-(F_{a,t}+M)},$$

where $\hat{R}_{r,m,1,t}$ is the estimated reported catch of tagged lobsters and $M = 0.24/12$ ^{-month}. Note fishing mortality in the unfished area is assumed to be zero ($F_{1,t} = 0$).

6.2.7 Likelihood of tag recoveries

A non-linear function minimisation procedure was used to estimate the values of the six migration parameters that maximised the likelihood of the observed tag recoveries. The parameters estimated represented the month-specific proportion of lobsters migrating from the unfished to the fished area, in each month from August to January ($P_{t=1-6}$). Initial parameter estimates used were 0.05 for each of the six months, i.e. 5%, of tagged lobsters migrated in every month. The negative log-likelihood (LL) of the observed recoveries of tagged lobsters (R) given by the monthly proportions of lobsters migrating (P_t) and our MSTR model was assumed to have a Poisson distribution (Hilborn 1990) and was represented by the equation:

$$LL = -\sum \left(-\hat{R}_{r,m,2,t} + R_{r,m,2,t} \left(\ln(\hat{R}_{r,m,2,t}) \right) - \ln(R_{r,m,2,t}!) \right).$$

The log-likelihood was maximised using the “optim” routine in “R”, with the square-R.t of the diagonal of the inversed hessian matrix, being produced to approximate the standard errors of the parameter estimates.

6.3 Results

6.3.1 Size class differences between unfished areas (>20 m) and fished areas (<20 m)

In Bahía del Espíritu Santo there was a significant difference ($P < 0.001$) in size composition between the lobsters found in the deeper unfished area (>20 m, area-II) and those in the shallower commercially fished bay (area-I). In the deeper area the mean CL of lobsters was 94.2 mm CL, with 99% of lobsters being larger than the minimum legal size (74.5 mm CL). In contrast, lobsters in the fished area (area I) had a mean CL of 73.0 mm, and 75% were smaller than the minimum legal size CL (Figure 6-2).

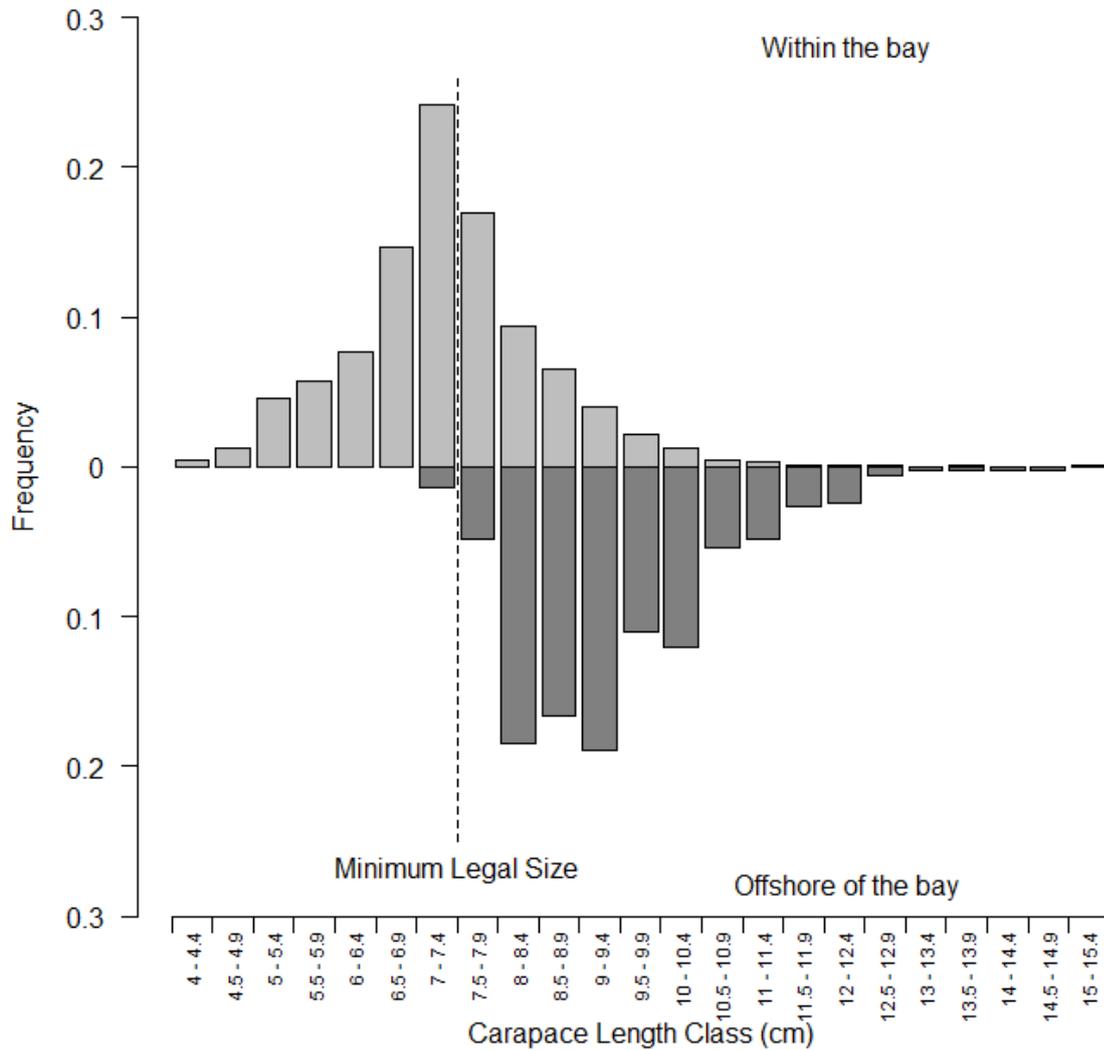


Figure 6-2 Graph showing the relative size frequency composition of *Panulirus argus* lobsters sampled within Bahía del Espíritu Santo, in the Biosphere Reserve Sian Ka'an-Mexico. Relative frequencies of carapace length (CL) in the fished shallow waters (<20 m) are depicted in light grey (top), and unfished offshore areas (depths > 20 m) in darker grey (bottom). The dotted line crosses the X axis showing the boundary between illegal and legal sized lobsters carapace length CL (74.5 mm CL).

6.3.2 Movements

Out of 379 lobsters released, 20 were recaptured (5.3%) within the fishery (area I) during the 2011/12 fishing season. A further four lobsters were recaptured within the fishery during the subsequent 2012/13 fishing season (total 6.3%). Recaptured lobsters comprised 50% females (average size: 85.9 mm CL, size range: 79.1-109.9 mm CL) and 50% males (average size: 101.4 mm CL, size range: 82.2-114.5 mm CL) and were caught over seven separate months starting from October 2011 (n=10), November 2011 (n=8), December (n=1) 2011, January 2012 (n=1) toward the end of the first season; and then July 2012 (n=2), November 2012 (n=1) and January 2013 (n=1) toward the end of the second season. Recaptured lobsters had mostly travelled in a southwest direction over distances ranging from 3.5 to 29.2 km when measured in a straight-line, with a mean distance of 7,602 m (Fig. 3). The lobsters recaptured in October 2011 were located near the fringing reef, whereas those recaptured in November and December 2011 had moved far greater distances and were found closer to the centre of the bay (Fig. 3). All of the lobsters recaptured in the second season following tagging (2012/2013) were captured near the fringing reef on the outside edge of the bay (Figure 6-3).

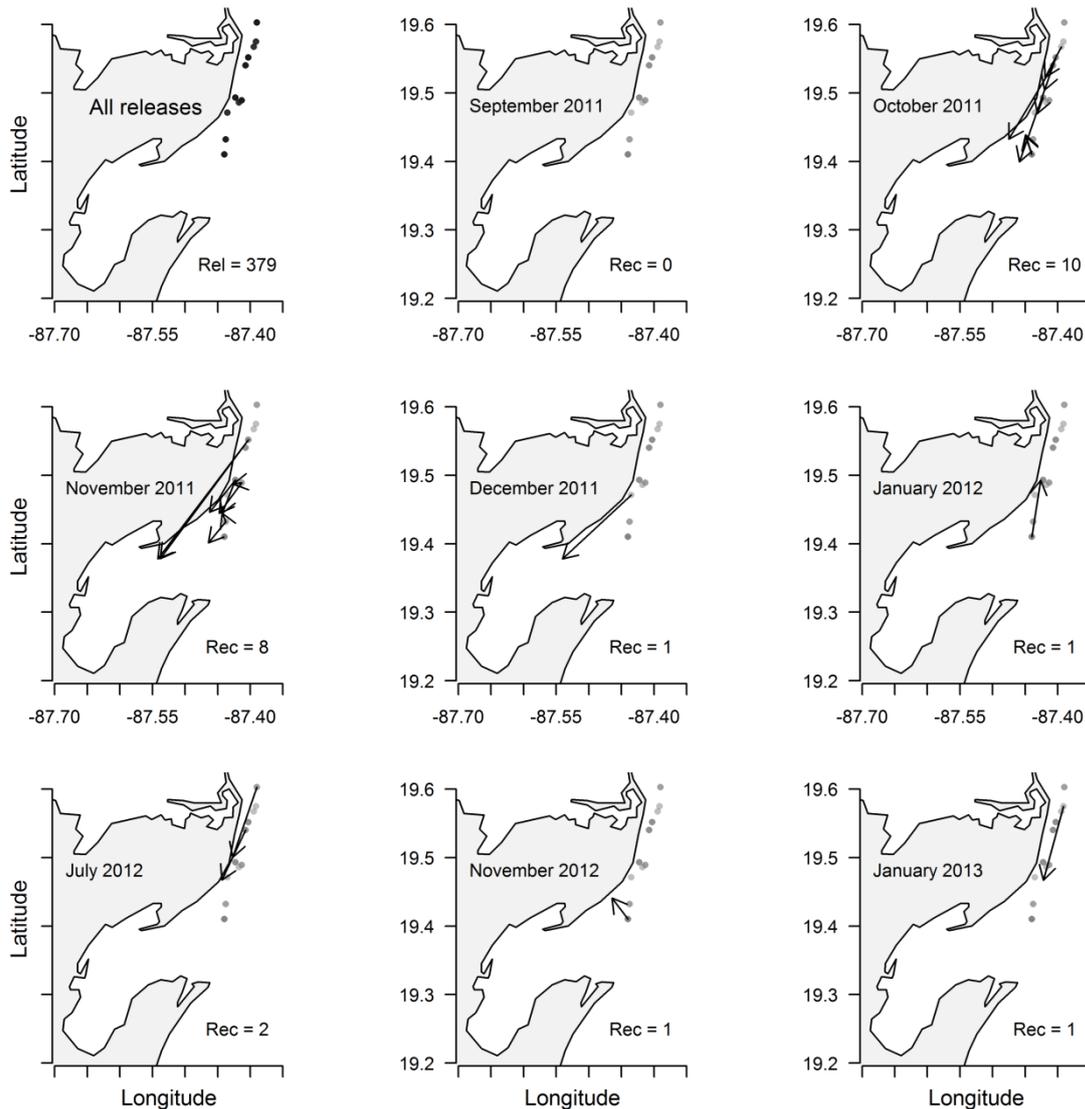


Figure 6-3 Shows a series of maps focusing on Bahía del Espíritu Santo (Southern bay) and Bahía de la Ascensión (Northern bay), in the Biosphere Reserve Sian Ka'an Mexico. It shows where lobsters were released (dots) and recaptured (arrows point) for each month in which the tagging program took place. Arrows show the distance and direction of lobsters travelling from the unfished areas (>20 m) where they were tagged, into Bahía del Espíritu Santo.

6.3.3 Catch trends, effort and catch rates for the inshore fished area

In Bahía Espíritu Santo, catch trends follow a similar pattern throughout the years, starting at the highest levels at the beginning of the fishing season in July, and progressively declining as the season advances towards the end in February. Catch per unit of effort

(CPUE) is also highest in July, after which it remains relatively constant from August to November, except for a second peak during the autumn- period. This latter peak in CPUE generally occurs in October or November and may be associated with the onset of the ‘Nortes’ (cold fronts arriving from the north).

6.3.4 Outputs of the model

Captures of lobsters from the two release pulses (i.e. August and September 2011) displayed similar patterns during the 2011/2012 fishing season, with no recoveries being reported prior to a peak in recaptures in October/November before progressively reducing through until January 2012 toward the end of the first fishing season. The MSTR model was able to recreate a very similar distribution of the tag recapture pattern observed in the fishery during the 2011/2012 season, also estimating tag recaptures peaked in October 2011 and declined slowly through until January 2012 (

Figure 6-4 and Figure 6-5).

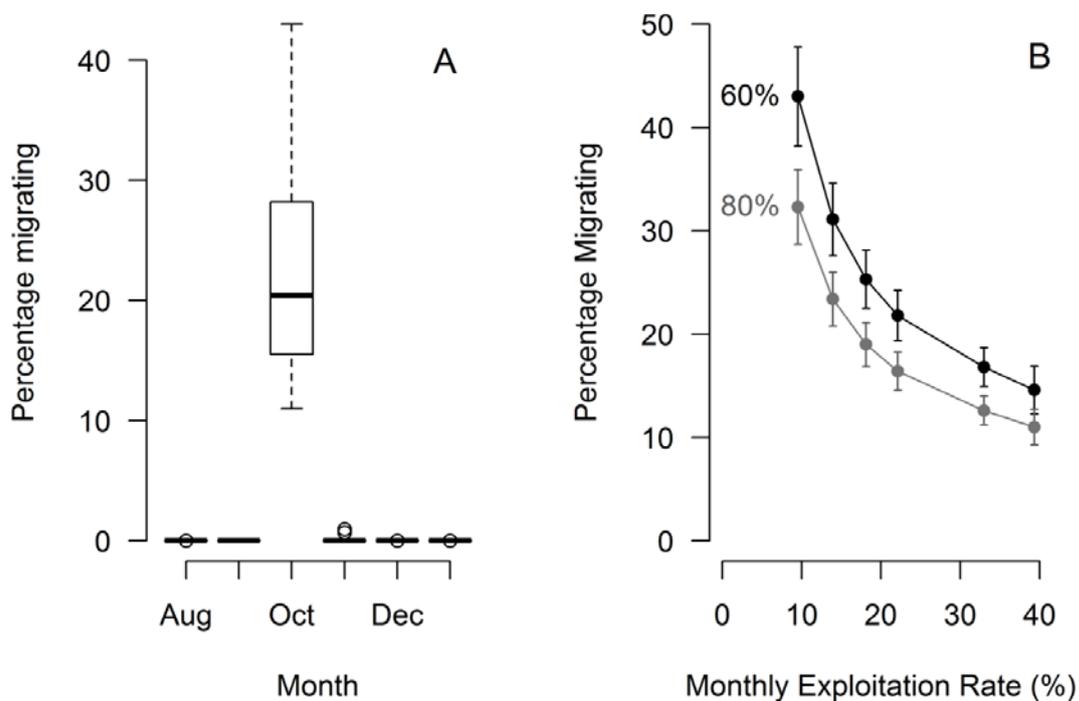


Figure 6-4: Results from the multi-state tag-recapture model modified from Hilborn (1990) and sensitivity analysis for the most likely exploitation rates and tag reporting scenarios.

(A) *Left panel:* Illustrates the most likely percentage of lobsters which migrate from the unfished-II areas towards the fished shallow bay -I, with a mean value of 20%, and range between 40 - 10%. Scenarios are based on data which replicate the observed tag recoveries under the most likely exploitation rates from the sensitivity analysis. The model simulations show that October is the month in which a most lobsters moved as in one pulse, with a very small probability of occurring in the other months (outliers are less than 2%).

(B) *Right panel:* Illustrates the percentage of lobsters which have migrated from the deep unfished areas-II, towards the fished shallow bay -I, as a result of the scenario outputs derived from multi-state tag-recapture model based on tag recapture data. The span of range values used in the sensitivity analysis was based on the most likely estimates for exploitation rates (0-40%) and tag reporting rates (60% and 80%) resulting in the simulation scenarios on the black and grey lines.

Under all sensitivity scenarios, a consistent pattern of migration from the unfished area (area-II) into the fished area (area-I) was estimated to have occurred as a single pulse during the month of October (

Figure 6-4 A). The proportion of lobsters estimated to have migrated had a median value of 20% and was relatively consistent across the majority of the scenarios tested for the different variables, i.e. ranging from 10 to 40%. The largest percentage of lobsters estimated to be migrating (~40%) occurred under the scenario of a low tag reporting rate (60%) and low exploitation rate (10%) (

Figure 6-4B).

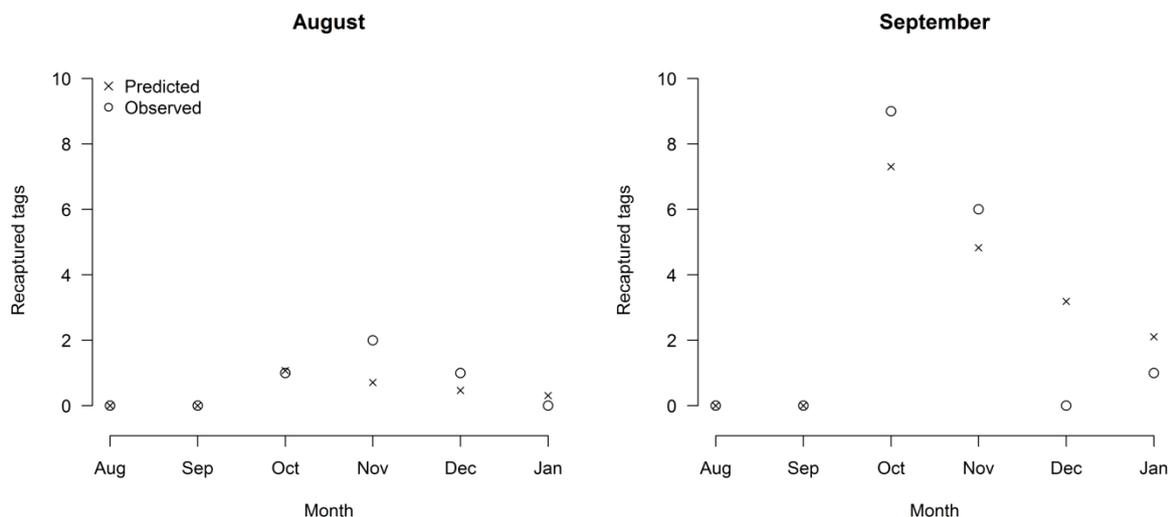


Figure 6-5: Shows the results derived from multi-state tag-recapture model which recreates the distribution of the tag recapture patterns observed in the fishery. Data was obtained from lobsters tagged in unfished areas-II offshore and recovered in the fished shallow bay-I in the study site of Bahía Del Espíritu Santo Sian Ka’an. The panels show the fitting of the observed against the predicted tag recapture patterns. The left panel corresponds to the batch of lobsters released during August and the right panel to the batch released in September within the unfished area-II offshore.

6.4 Discussion

Results from this study suggest that legal sized lobsters (sub-adults 74.5-80.0 mm CL and adults >80.0 mm CL) move from the offshore unfished area and enhance the commercially

fished area in the shallows within the SK-BR. The movement rates of the tagged lobsters were examined using a purpose built multi-state tag-recapture model, which was able to replicate the observed tag recoveries obtained from the commercial fishery. Based on an assumed monthly rate of fishing mortality 30% (which was reported the previous season e.g.; Ley-Cooper *et al.*, 2013), and a rate of tag-reporting of 70%, about 20% of the lobsters originally dwelling offshore migrated into the bay. Sensitivity analysis indicated that if the assumptions for fishing mortality and tag reporting were varied within sensible ranges the proportion estimated to be migrating did not vary radically, generally remaining within the range of 15 – 20%.

The model estimated that the movements all occurred within the same month, (October 2011), a period within that year that coincided with the start of a cold front system, as well as an annual increase in the catch per unit of effort in the commercial fishery of both the north and southern bay of the Biosphere Reserve (Ley-Cooper *et al.*, unpublished data). The movement of spiny lobsters has been well documented for many spiny lobster species and has been generally categorised into three types, homing, nomadic or migratory movements (Herrnkind 1980, Phillips 2006). Migratory movements are unidirectional, occur in mass quantity, during a confined period of time, and have been attributed to several factors such as ontogenetic behaviour; seasonal movements towards feeding grounds (Acosta 1999, Briones-Fourzán *et al.* 2003, Ríos-Lara *et al.* 2007); spawning migrations (Bertelsen 2013); or as a response to environmental stimuli such as moon cycles, changes in water temperatures, and changes in wind strengths and direction (García *et al.* 1991). In Florida, Bahamas and Cuba, movements of *P. argus* were reported to be initiated by cold fronts in autumn, as increasing wind speed and direction increased water turbidity and decreased water temperature, which in turn triggered lobster mass migration behaviours (Herrnkind 1980, Herrnkind 1985, García *et al.* 1991). Data from 1984 to 2012 from the northern bay of SK- Bahía de la Ascensión has shown that an increased Meridional wind speed and change of direction results in a direct relationship with increased catch rates during the autumn period (Ley-Cooper *et al.*, unpublished data). Using CPUE as an indication of abundance, a plausible hypothesis is that cold fronts generate additional nomadic movements of lobsters due to changes in temperature, and increased turbidity which allows for greater foraging distances, which may result in movements from the deep (area II) to the shallow bay (area I). The model estimated that most movements occurred as a single pulse, which suggests that a migration-like behaviour could have been the causative factor.

Regardless of the motive, the lobster movements (mainly large adults see Fig.2) from an unfished offshore area into the shallower commercially fished bay is contrary to the general pattern of migration observed in spiny lobsters, since the paradigm is usually small immature lobsters moving offshore as part of their normal ontogenetic behaviour (Briones-Fourzán et al. 2003, Melville-Smith & de Lestang 2006, Phillips 2006). Movements of juveniles and adults within the bay and towards offshore areas have also been documented in previous tagging studies in this area (Ley-Cooper *et al.*, 2013), yet the migration of these large lobsters from the deep offshore towards the shallow bay had not previously been documented.

In a previous study conducted in Bahía de la Ascensión (BA) (see Fig 1), (Lozano-Álvarez, *et al* 1993) suggested that adult lobsters probably returned to that shallow bay after breeding in offshore areas of the deeper shelf. González-Cano (1991) analysed recruitment using size structure and catch data, suggesting that seasonal migrations from deep to shallow areas could occur annually as lobsters are re-distributed in Isla Mujeres (further north) (Fig 1). The latter study supports our findings in this assessment, but the use of a multi-state tag-recapture model as the one presented here had additional benefits, as it was able to provide an estimate of the proportion of the population moving into the bay, a measure that is particularly useful for conducting spatial stock assessments (Ziegler et al. 2003 , Goñi et al. 2010, McGarvey et al. 2010).

Lobsters which had previously been tagged in Bahía de la Ascensión (BA) have also been recaptured in Bahía Del Espíritu Santo. These movements took two years, with lobsters covering a distance of about 43.5 km (Ley-Cooper *et al.* 2013). Whether the lobsters tagged for this study originated in BA when they started to migrate remains unknown, yet the estimated 15-20% proportion indicates that recruitment into these fisheries from deep waters occurs, and that there is some level of offshore adult connectivity after 20 m depths between both bays of the SKBR.

This migration also provides new evidence for the potential maintenance or enhancement of fishing yields into areas which are adjacent to unfished reserves. In the two bays of the SK- BR maximum catch rates are observed as peaks at the beginning of the fishing season in July, and in the mid-season during autumn, between October and December (Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013). Fishing exploitation rates are high within the shallow-bay area, and results of this study suggest that in order to sustain such high catch rates in autumn, lobsters recruited to these fisheries must be partially replenished by both

juvenile growth (moulting from undersize to legal sized lobsters) (González-Cano 1991, Lozano-Álvarez et al. 1991b, Lozano-Álvarez et al. 1993, Briones-Fourzán et al. 2007, Ley-Cooper et al. 2013), and by the input of lobsters moving in from unfished areas found offshore in deeper waters (>20 m). The contribution to catch rates within Bahía del Espíritu Santo that were derived from growth, movements, natural and fishing mortality had been previously explored and reported (Sosa-Cordero et al. 1999, Ley-Cooper et al. 2013), yet the proportion of migrating lobsters from the deeper unfished areas had not been estimated, or described as a source of recruitment.

The significant difference in the size composition of lobsters between the deep unfished and shallow fished areas may be attributed either to ontogenic movements such as juvenile progressive growth and migration offshore (Lozano-Álvarez et al. 1993) and/or the high rates of fishing mortality of legal sized lobsters which only occurs within the commercially fished bay, since causes of natural mortality are generally independent of depth and most likely similar in both areas (Ley-Cooper et al. 2013).

A number of factors could have biased our estimates of migration in this study, including the relatively small sample size of recaptured lobsters. It would be advantageous, should the study be repeated, if a significantly greater number of lobsters were to be tagged. Tag loss is also an area where a bias may be incorporated. The rate of tag loss used in this study was based on that determined from aquaria trials and therefore may not directly mimic that which may have occurred in the reserve during our study. Different water quality, lobster densities and habitat availability all could have caused the tag loss rate to have differed. A decreased rate of tag loss would have biased our results and increased the estimate of the proportion of lobsters migrating. Future work in this area could include the double tagging a number of the individuals released to examine *in situ* tag loss.

Although tags continued to be returned during the following season (2012/2013), their numbers were too low to be added into the model. The two tags returned at the start of the second season may have been from lobsters that migrated into the bay either during the closed season (February–June) or during the previous October (2011) and survived fishing mortality during the remainder of that season. It is interesting that no other tagged lobsters were recaptured within the bay until November 2012, five months into this second season, at a point when over 70% of the season's annual catches had been landed. It is possible that the lobsters recaptured in November 2012 and January 2013 did not enter the bay during October

2011, but rather during a second autumn migration occurring in the October/November 2012. The lack of robust information provided by these 2012/2013 tag returns highlights the value of continuous studies of this nature. A series of yearly multi-release tagging campaigns in both the fished and unfished areas is recommended for the future, which could provide annual estimates of the overall biomass contributed to the fishery by the lobsters migrating into the bay.

According to the model produced in this study the larger proportion of the deep segment of the population remains unfished, and we suggest that in the SKBR the deep areas (>20 m) should remain as such. In order to guarantee a sustainable management of this fishery and the conservation of the *P. argus* lobster population, it would be advantageous to understand the variations on the yearly proportions of large lobsters moving from the unfished areas into the shallow areas subject to fishing, and the effects that this may have on the biomass of the total stock. It is recommended that these issues be further addressed in future studies.

7 CHAPTER 7 Environmental effects derived from cold fronts increase catch rates of spiny lobsters in a Mexican Caribbean Biosphere Reserve fishery

Running page head: environmental cold front effects on Caribbean lobsters

Kim Ley-Cooper^{1*}, Simon de Lestang², Patricia Briones-Fourzán³, Enrique Lozano-Álvarez³, Bruce F. Phillips¹, Ravi Fotedar¹, (*submitted for review*). Environmental effects derived from cold fronts increase catch rates of spiny lobsters in a Mexican Caribbean Biosphere Reserve fishery.

7.1 Introduction

The *P. argus* (Latreille, 1804) is one of the most valued fishing resources throughout the Caribbean region, but due to high levels of fishing pressure, most fisheries for *P. argus* are currently depleted (Seijo 2007, Ehrhardt et al. 2011). An exception is the fishery for lobsters in Bahía de la Ascensión (Sosa-Cordero et al. 2008), the larger of two bays within the Sian Ka'an Biosphere Reserve (SKBR), located on the Caribbean coast of the Yucatan peninsula (Mexico). The fishery for lobsters in SKBR is based on the extensive use of casitas, large artificial shelters where the highly gregarious *P. argus* lobsters congregate. In 2012 the SKBR lobster fishery was certified as being sustainable by the Marine Stewardship Council (MRAG Americas 2012). Yet, a component of this certification was the requirement for additional assessments to evaluate whether current catch, target biological reference points, fishing effort, and exploitation rates are appropriate and will ensure that the fishery is sustainable.

Throughout most fishing seasons (July to February), the lobster fishery in Bahía de la Ascensión exhibits a decreasing trend in catch rates, with maximum values in July, when the season opens, and a rapid decline that then levels off at relatively low levels as the fishing season progresses (Lozano-Álvarez et al. 1991). However, at some point during the autumn months (September to early December), there is usually an atypical increase in catch rates. Throughout most of the year, easterly (trade) winds dominate along the Caribbean coast of Mexico except for relatively short periods during the autumn and winter, when northerly winds (cold fronts) cross the Yucatan peninsula from north to south (Merino & Otero 1991). Anecdotal evidence suggests that the autumnal increase in catch rates in BA coincides with the onset of strong cold fronts (locally known as “Nortes”). It is well documented that the available biomass of lobsters can be altered by variations in environmental factors (e.g.

(Herrnkind et al. 1973, Puga et al. 2013) Herrnkind et al. 1973, Puga et al. 2013). In Australia, for example, changes in water temperature and lunar illumination affect the foraging behaviour and hence the catchability of western rock lobsters *P. cygnus* in baited traps (Srisurichan et al. 2005, de Lestang et al. 2009). In south-western Cuba, in response to sudden decreases in air temperature and changes in wind direction associated with the passage of cold fronts or tropical storms, catch rates of *P. argus* tend to decrease in shallow waters (<10 m in depth) and to increase in deeper waters (>10 m in depth) (García et al. 1991). In the area of Isla Mujeres (Mexico), González-Cano (1991) reported increases in catches of *P. argus* at depths greater than 10 m after the passage of cold fronts.

Panulirus argus is a highly mobile species and the movement range of these lobsters tends to increase with increasing size. Subadult and adult lobsters may take residence in a relatively small reef or hard-bottom area for days or weeks at a time, exhibiting foraging movements of tens to hundreds of meters per night followed by return to their residence area (Herrnkind et al. 1975, Lozano-Álvarez et al. 2003, Bertelsen 2013). However, variations in environmental factors and/or changes in behaviour may encourage lobster movements, and *P. argus* lobsters have been shown to move as much as 200 km in less than a year (Davis & Dodrill 1989). Movements may change lobster abundance and hence affect catch rates in local fisheries (e.g. García et al. 1991, González-Cano 1991, Ziegler et al. 2003, de Lestang 2014); therefore, stock assessments based on catch per unit of effort need to take into account determinants of changes in activity and movement patterns of the focal species (Smith et al. 1999). For example, environmental factors that affect catches of different species of lobsters by inducing movements include large swells (*P. cygnus*: Srisurichan et al. 2005; *P. ornatus*: Tewfik 2014), changes in temperature (*Jasus edwardsii*: Ziegler et al. 2003), along-shore winds that may create upwelling or downwelling (*Homarus americanus*: Drinkwater et al. 2006), low light levels caused by increased turbidity induced by waves and water movement at the seabed (*H. gammarus*: Smith et al. 1999), and changes in salinity (*P. cygnus*: Morgan 1974, *P. polyphagus*: Rao & Kathirvel 1971). In certain locations *P. argus* lobsters exhibit mass migrations after the passage of strong autumnal storms (Nortes), which are associated with increased water turbulence, turbidity, and swell (Herrnkind et al. 1973, Kanciruk & Herrnkind 1978, Herrnkind 1980), and fishers capitalize on these migrations by making large catches (González-Cano 1991, Baisre 2000, González-Yáñez et al. 2006).

Lobster movements may also help to maintain or enhance catch rates in areas adjacent to unfished areas (e.g. marine reserves) (Russ and Alcala 1996; Goñi et al. 2006). This may be

the case in SK, where fishing for lobsters is conducted at depths <20 m but lobsters occur to depths in excess of 50 m along the unfished offshore area (Lozano-Álvarez et al. 1993). A tagging study in the unfished area off Bahía del Espíritu Santo, the smaller of the two bays in SKBR, showed that a shoreward movement of lobsters occurred during autumn and may have contributed to an increased catch rate in the shallow water casita-based fishery following that period (Ley-Cooper et al. 2014). The possibility of an environmentally induced movement from the unfished area (>20 m) to the fished area in the SKBR requires a critical analysis for outlining future management changes, since these dynamics may occur independently of the stock biomass condition.

In this paper we hypothesize that during autumn, there is a positive correlation between the increased lobster catch rates and the passage of Nortes, which in turn increase wind strength from the north and decrease water temperatures. Using 25 years of data, we assessed the inter-annual variability of the timing of the increase in catch rates during the autumn period, and compared this with the timing of changes in temperature, wind speed and direction, as these are potential environmental factors that may underlie changes in catch rates.

7.2 Materials and Methods

7.2.1 Study Site and Fishery Characteristics.

The SKBR is located on the central coast of the State of Quintana Roo., in the Mexican coast of the Caribbean Sea. The present study was based in Bahía de la Ascensión (BA), which is the northern bay of SKBR. BA is a large (~740 km²) and shallow (<6 m deep) bay, bordered by mangrove and grass swamps, with a substantial part of the bottom covered with seagrass (mainly *Thalassia testudinum*) and dense aggregations of red and green algae. A coral reef tract runs parallel to the mouth of the bay, protecting its inner waters from wave surge (Lozano-Alvarez et al. 1993). Seagrass, mangroves, and coral reef patches comprise favourable habitats for settlement and growth of *P. argus* (Briones-Fourzán et al. 2000; Sosa-Cordero et al. 2008). Due to the karstic landscape, BA has a large drainage basin and hence behaves like an estuary with an intense water exchange across the bay's inlets located along its mouth (Medina-Gómez et al. in press). Annual sea surface temperature (SST) in SKBR ranges between 24.4 to 32.2 °C, with periods of low temperature occurring between the months of October and March, which are commonly associated to the passage of Nortes (Briones-Fourzán 1994). Nortes begin to affect BA in autumn, mainly during October and November (Briones-Fourzán 1994) and are easily detected as a marked sudden increase in

wind speed occurs with a change in direction from the north. Nortes are also preceded by a calm or short windless period (≤ 24 hours) after which wind direction changes abruptly and the Nortes generally last between two and five days (Merino and Otero 1991).

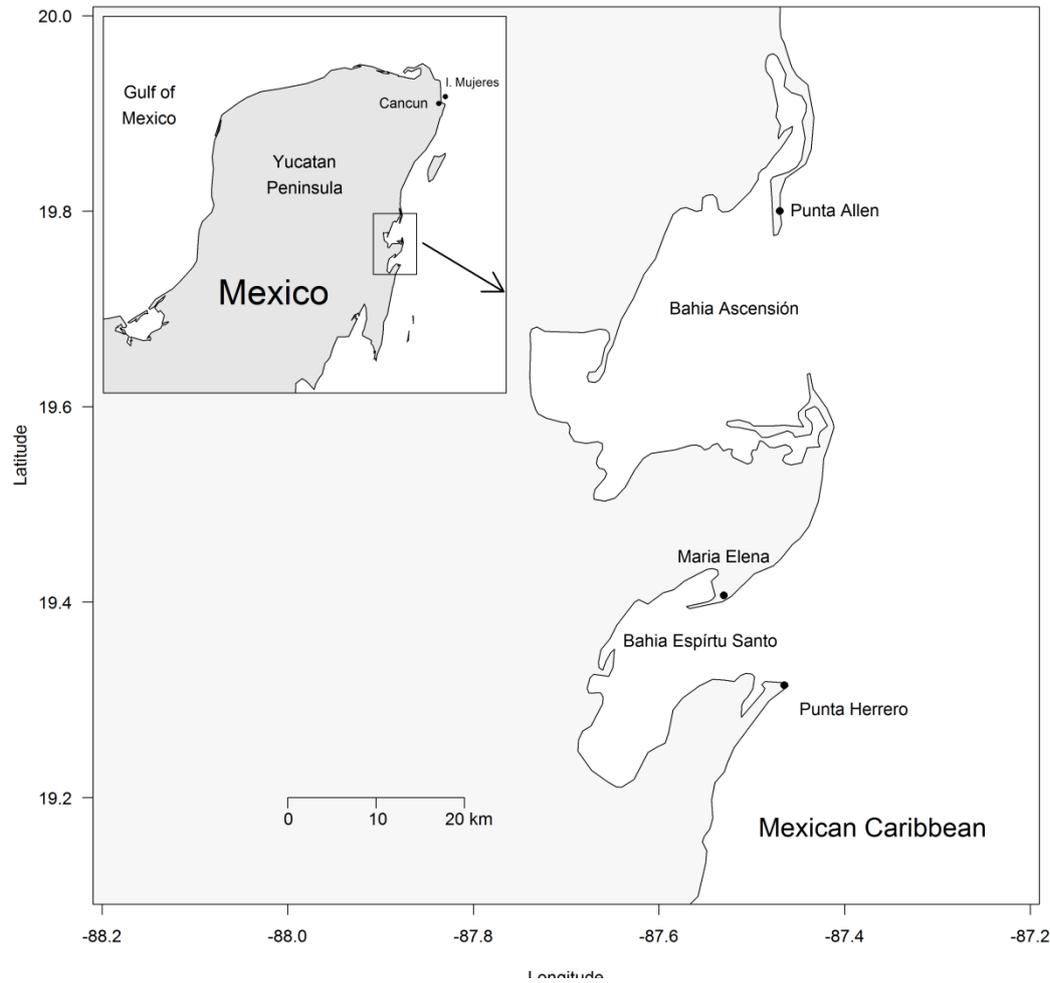


Figure 7-1: Map showing the Mexican Yucatan Peninsula and the study area, Bahía de la Ascensión, which is the northern bay of the Sian Ka’an Biosphere Reserve. The box surrounding the study area on the map of the Yucatan represents the area for which environmental variables were restricted

Sustainable productive activities by local inhabitants are allowed within biosphere reserves. Thus, fishing activities are allowed in the SKBR and are co-managed by the federal environmental and fisheries government authorities, and the local fishing cooperatives. The *P. argus* lobster fishery is based on a “campo/casita” system, which consists on partitioning the fishing areas in the bay into parcels (“campos”) which vary in size from areas of 3 km² to 20 km², that are allotted to individual fishers. Fishers are free to deploy as many “casitas”

(artificial shelters) as they see fit within their campos, but adjacent casitas are typically separated by approximately 30 to 50 m. Using small boats, fishers check their casitas by skin diving and collect legal-sized lobsters (13.5 cm tail length, ~74 mm carapace length, CL, Lozano-Álvarez et al. 1991) using hand nets. The catch consists mainly of large sub-adult (up to 80 mm CL) and adult lobsters (>80 mm CL) that inhabit the shallow fishing areas within the bays. Fishers whose campos are adjacent to the coral reef tract also skin dive in the coral reef to extract lobsters by hand down to ~15 m in depth. However, most of the adult lobsters in the population inhabit deeper coral reef and offshore areas of the narrow continental shelf (Lozano-Álvarez et al. 1993). These deeper areas (>20 m in depth) are not fished because SCUBA diving and the use of traps are prohibited in this area. The fishing season for *P. argus* in Mexico opens on 1 July and closes on the last day of February of the following year. This fishery is described in greater detail in Lozano-Álvarez et al. (1991), Briones-Fourzán et al. (2000), Sosa-Cordero et al. (2008), and Ley-Cooper et al. (2013).

7.2.2 Determining Catch per Unit of Effort: (CPUE).

Historical daily catch and effort data from Bahía de la Ascensión was obtained from the local fishing cooperative “Pescadores de Vigía Chico” for the fishing seasons 1986–87 to 2010–11, except for five seasons that were unavailable (1988-91, 2002-03, 2005-06). Specific catch and effort data from 2000 to 2011 were cross-checked against accountability tax files containing catch details for every associated fisher, as well as data sets from governmental agencies and source files from the National Fisheries Institute (Mexico).

Previous studies examining the commercial catch rates of *P. argus* in Bahía de la Ascensión have used the total number of fishing trips per time period as a measure of effort (Lozano-Álvarez et al. 1991; Sosa-Cordero et al. 2008). The appropriateness of catch rate derived from this measure of effort as an indicator of exploitable biomass is related to the extent to which two main assumptions are met, namely that both lobster catchability and fisher behaviour remain constant throughout the fishing season. Since in Bahía de la Ascensión lobsters are predominantly caught using casitas, a method with a selectivity that is unbiased by lobster activity, it is fair to assume that lobster catchability in this fishery remains relatively constant. Although the behaviour of fishers changes during the fishing season, even between successive fishing trips, in response to changes in environmental conditions such as wind and water turbidity, it does not appear to change in a progressive fashion; rather it varies in a consistent manner throughout the fishing season. This variation would have biased

catch rates slightly by adding some error; however, the consistency of its variation throughout the season would not have impacted the index which we derived from the catch rates. The indicator of when a migration of legal lobsters entered the fishery is the timing of a marked and progressive positive change in catch rate trajectory.

7.2.3 Spatial distribution of the CPUE.

Determining the spatial extent of each campo and assigning historical catches to the correct campo required the identification of current and previous ownership by using information from the fishing cooperative and on-site interviews. For these purposes, the bay was divided into 18 locations based on the colloquial names used by the fishers, with each location containing a number of neighbouring campos and in some cases areas of the coral reef. The limits of each location were based on the presence of geographical boundaries such as mangrove islands, channels, reef patches or sand banks which in all cases also coincided with campo boundaries.

7.2.4 Identifying yearly trends and the timing of autumn increases in CPUE;

Standardised (geometric) catch rates for each of the 18 locations for each half-month (days 1 to 14 or 15+) and fishing season were determined as not all campos in every location were fished in every month-year combination. The standardised catches rates were produced by modelling the location specific monthly and yearly trends in catch rate with a Generalized Linear Model (GLM) in the software package R (R Development Core Team 2012). Geometric means were then produced using the `predict.glm` function.

To examine variation in the timing of marked increases in catch rates, the standardised catch rate for each location-month combination (seasons pooled) was first examined individually to determine whether that location displayed the specified catch rate trend (step 1). All locations determined to have displayed this catch rate pattern were then combined into a single dataset (locations pooled) and remodelled using a GLM to produce standardised means for each year-half month combination to allow for a finer scale fishery-wide timing of catch rate increase to be determined for each fishing season (step 2). To allow for a catch rate increases to be determined on a finer scale, mid points between consecutive half month estimates (i.e. quarter-month estimates) were determined from the average to the two adjacent half month estimates. This resulted in catch rate estimates for every quarter month for each fishing season.

Step 1. A second-order polynomial was fitted to the monthly standardised catch rate data for each location for the months of October to February (mid-autumn to end of winter period), to determine how catch rates changed during the autumn period of the fishing season, i.e. a positive, negative or neutral change. The equation used was:

$$R = \alpha M + \beta M^2 + \gamma, \quad \text{Equation 7-1 Eq. 1}$$

where R is the standardised catch rate (kg/trip) and M is the month into the season (e.g. July = 1, August = 2 ...). The first-order coefficient (α) was used to categorise each location based on its trend in monthly catch rates: either catch rates declined progressively before increasing at the end of the season ($\alpha < 1$); declined progressively through until the end ($1 < \alpha \leq 10$); or showed a marked increase in autumn ($\alpha > 10$). See Figure 2 for specific examples.

To determine if there was a geographical pattern to the locations that exhibited each of the different trends in monthly catch rates, all campos from each location were plotted on a spatial map with their associated location α level used to colour code them. The position of campos exhibiting each characteristic of catch rate patterns was then assessed based on their proximity to each other and bathymetric characteristics such as fringing reefs, water depth, and distance from the centre of the bay.

Step 2. A more complicated model was fitted to the quarter-monthly catch rate data to estimate of the timing of catch rate increase. The model used was a fourth-order quadratic equation:

$$R = \alpha H + \beta H^2 + \gamma H^3 + \delta H^4, \quad \text{Equation 7-2 Eq. 2}$$

where H corresponds to each half-month period (e.g. 1st–15th July = 1, 16th–31st July = 2, etc.) during the season months July–February. During the autumn months of the fishing season, the maximum first derivative of this polynomial was used to determine the timing (quarter-month) when catch rates most rapidly increased.

7.2.5 Environmental variables.

To determine whether environmental variables were related to the timing of the marked increase in catch rates determined for each year in Bahía de la Ascensión, we examined the timing of changes of monthly mean meridional and zonal wind strength and monthly mean SST. The environmental data sets were obtained from the NCEP reanalysis, provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at

<http://www.esrl.noaa.gov/psd/> (Kalnay et al. 1996). These data covered the study site with a latitudinal range of 19°00'N–20°00'N and a longitudinal range of 87°00' W–88°00' W (see insert in Fig. 1). To allow for variable changes in the environment to be determined on a finer scale, mid points between consecutive monthly estimates (i.e. half-month estimates) were determined from the average of the two adjacent monthly estimates. This resulted in environmental estimates for every quarter month throughout the time series.

The timing (closest half month) of wind and SST values, breaching a range of threshold levels that encompassed the historic range of each variable during autumn and winter were determined. An average threshold value (ATV) is defined as the average value during one half of a month (i.e. approximately 15 days). It should be noted that positive and negative values of meridional wind represent air moving in northward and southward directions, respectively, whereas positive and negative values of zonal wind represent air moving in eastward and westward directions, respectively. ATVs ranged from -0.5 to -2.5 ms⁻¹ for meridional (northerly) wind speeds, from -1.5 to -3.5 ms⁻¹ for zonal (easterly) wind speeds, and from 27.0 to 29.0°C for SST. The wind ATVs were examined in 0.1 ms⁻¹ increments, and the SST ATVs were examined in 0.1°C increments. To determine the most likely timing (half month) when an ATV was breached by an environmental index, a cubic spline was fitted to the half monthly data using the “zoo” library on the “R” platform. The closest half month interval that occurred following the point when the cubic spline beached the ATV was considered as the time when the ATV was achieved.

7.2.6 Environmental factors correlation to timing of CPUE increase.

The relationships between annual variation in the timing of each environmental threshold being breached and that year's marked increase in catch rate were examined individually using a linear model, with the resultant R^2 and significance level of the relationship determined. These outputs were then used to ascertain which environmental factor, and at what threshold levels, had the greatest relationship with the timing of catch rate changes.

7.3 Results

7.3.1 Catch Rates

The patterns displayed by monthly catch rates between August and February varied among the 18 fishing locations in Bahía de la Ascensión (

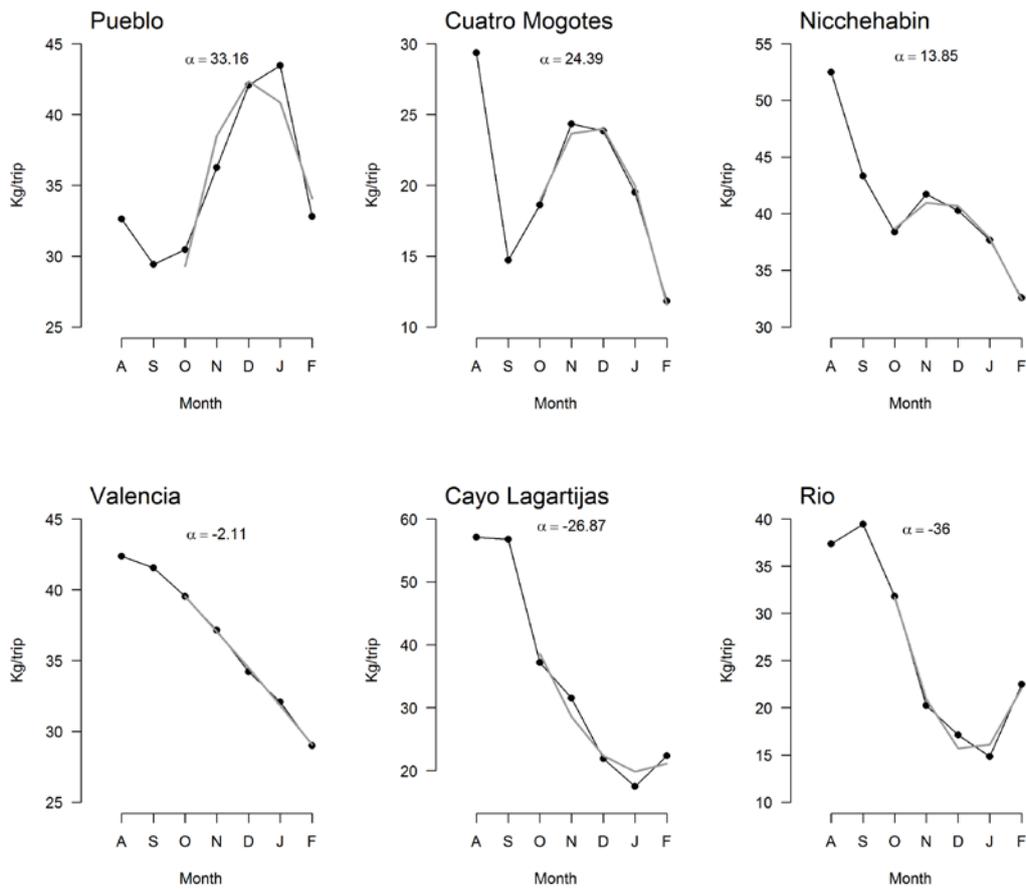


Figure 7-2). Note that July catch rates were not plotted in Fig. 2 because their magnitude dwarfed subsequent catch rates, making it difficult to distinguish changes in their trajectory. A number of locations showed dramatic increases in catch rates in October–December, with catch rates in some locations remaining higher than September levels throughout and until the end of the fishing season in February (e.g. location “Pueblo” in

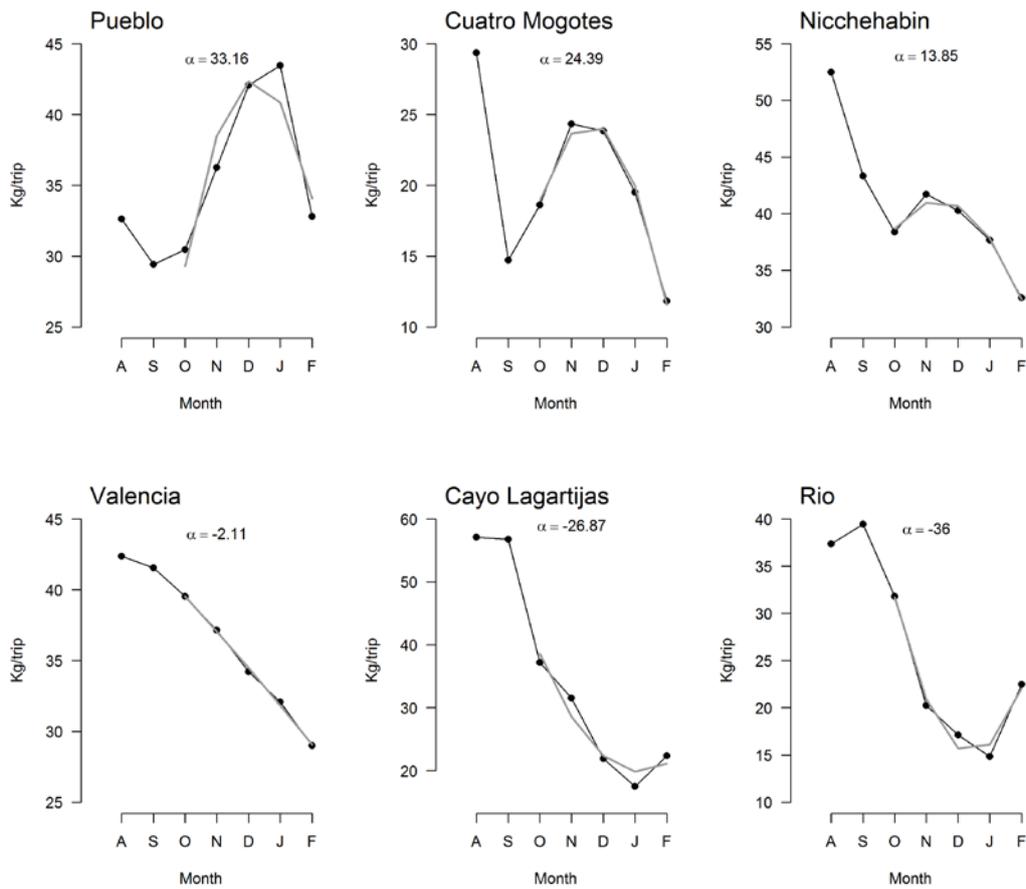


Figure 7-2). All sites that displayed marked increases in catch rates in autumn were described by a high 1st order coefficient (α) from the polynomial model. In cases when the decline in catch rates was progressive, continuing on the same trajectory throughout the fishing season without an obvious increase in the catch rates occurring, the fitted polynomial had little deviation from linear and the model-derived α was very close to 0 (e.g. location “Valencia” in

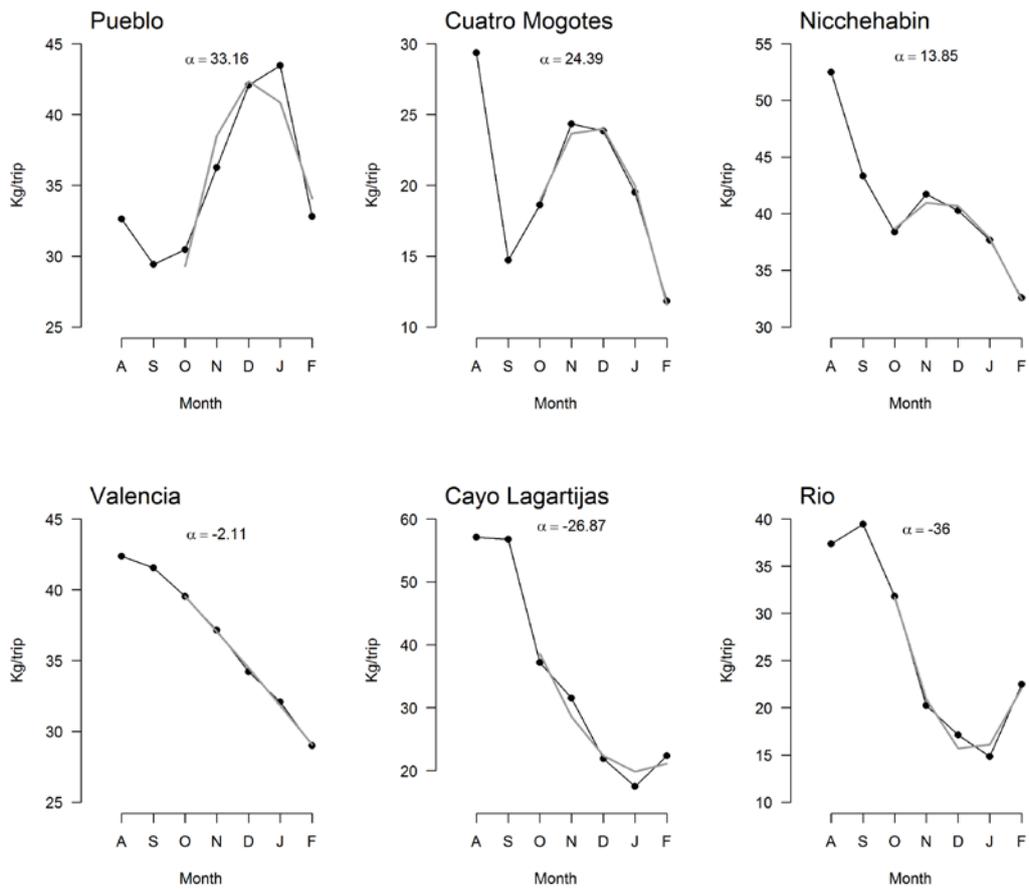


Figure 7-2). A number of sites displayed a progressive decline through the season to very low catch rates before showing an increase at the very end of the season in February. In these cases the polynomial returned a negative α coefficient (e.g. locations “Cayo Lagartijas” and “Rio” in

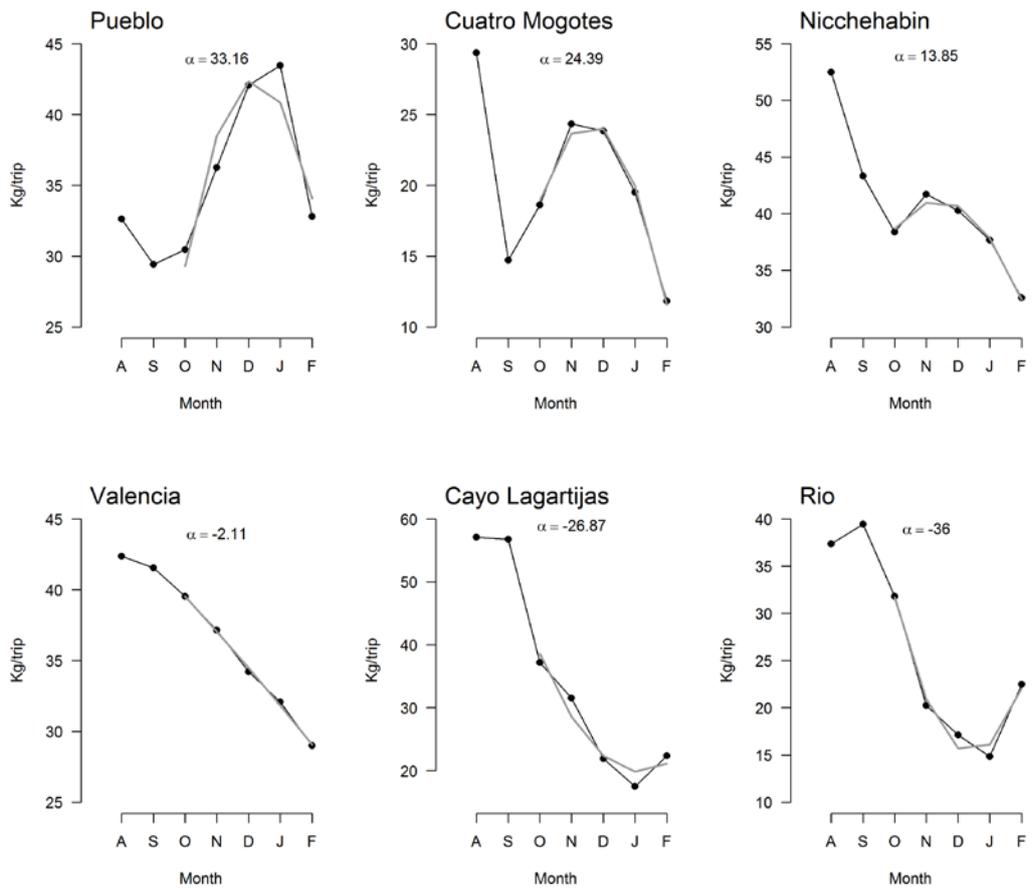


Figure 7-2).

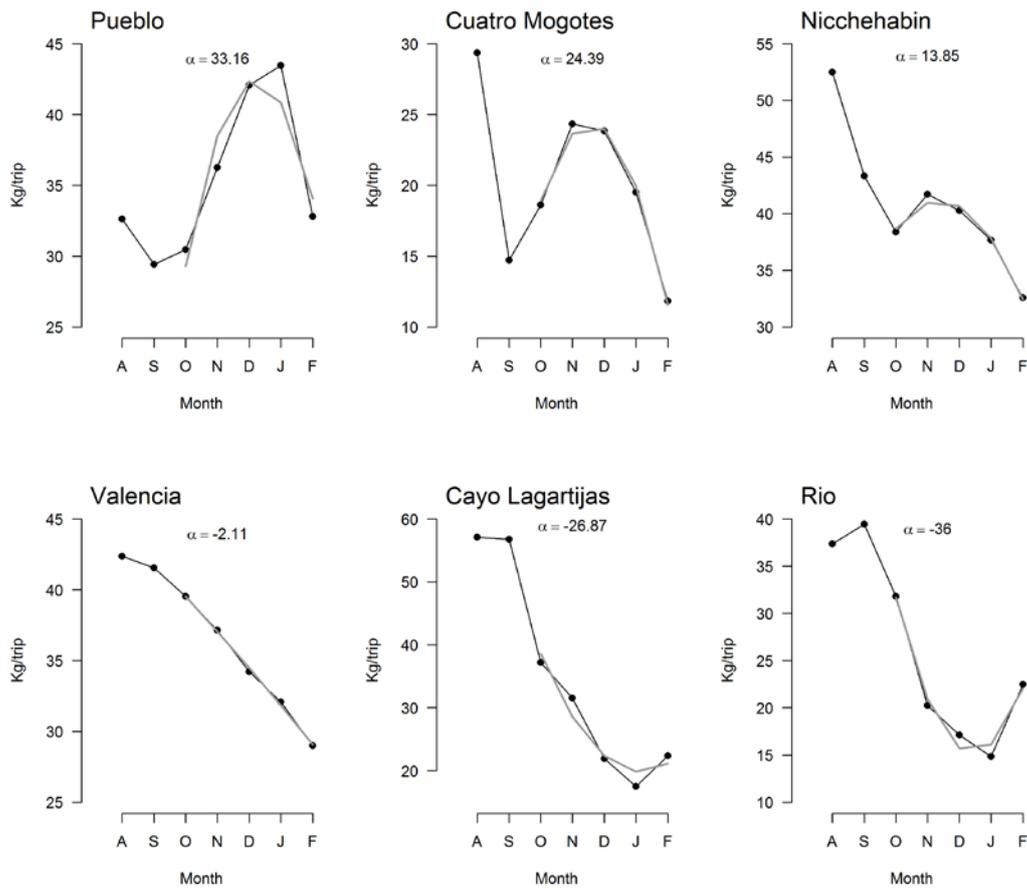


Figure 7-2: Examples of monthly catch rate (kg/trip) trends (black) and 2nd order polynomial models (grey) fitted to catch rates from August to February in six of the 18 fishery locations of Bahía Ascensión. July was removed because the magnitude of the catch rate in this month dwarfed the rest. α represents the 1st order coefficient of the model and describes the extent to which the model inflects upwards during the mid-autumn to early winter period (i.e. representing an increase in catch rates during this period)

7.3.2 Spatial distribution of catch rates

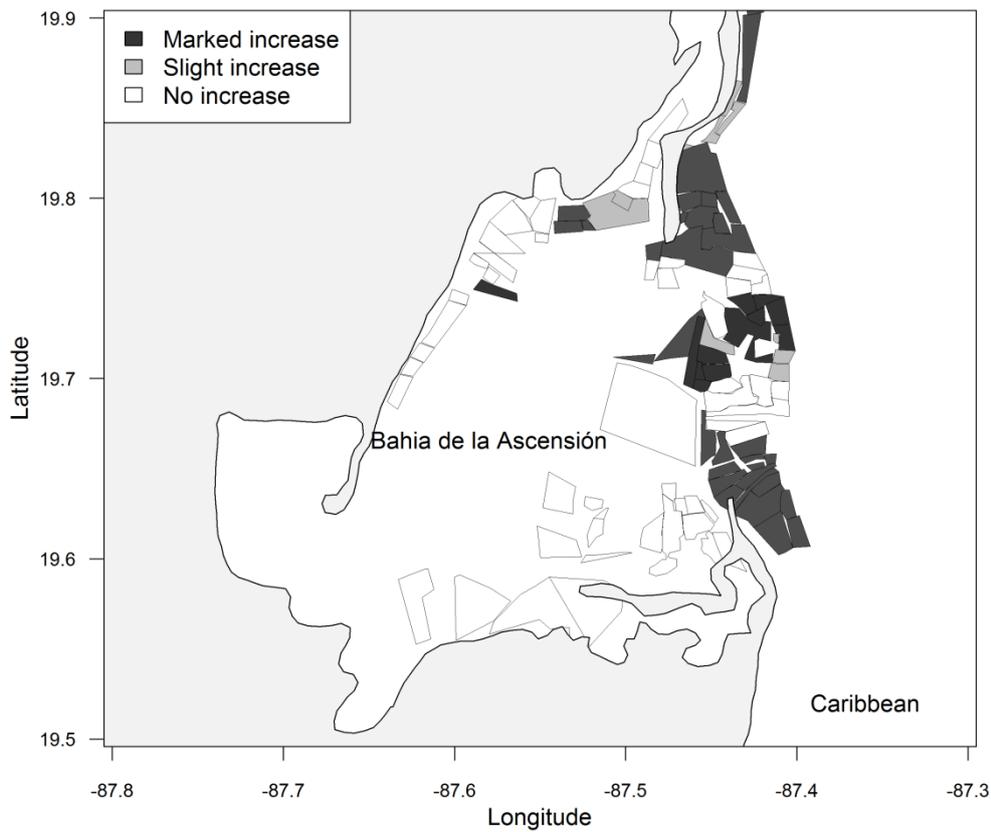


Figure 7-3: Map of Bahía de la Ascensión lobster fishery identifying those “Campos” which showed a marked increase (dark grey), a slight increase (light grey) or a decrease (no colour) in catch rates during the autumn/winter period. The easternmost boundary of the Campos is constituted by a coral reef tract

The 18 fishery locations in Bahía de la Ascensión, which comprised 111 Campos in total, displayed a distinct pattern when colour-coded to identify catch rate trends during the autumn

months of the fishing season (

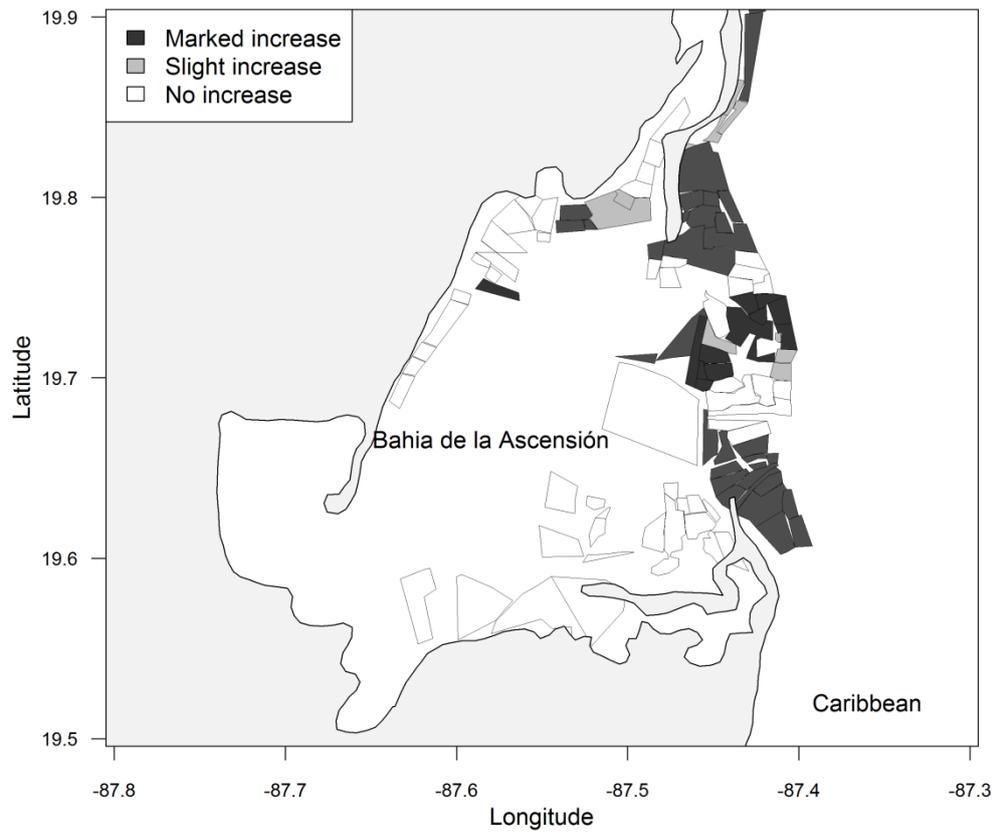


Figure 7-3). The majority of locations that displayed marked increases in catch rates during autumn, as determined from the polynomial model, were located towards the eastern side of

the bay adjacent to the coral reef (identified as dark grey in

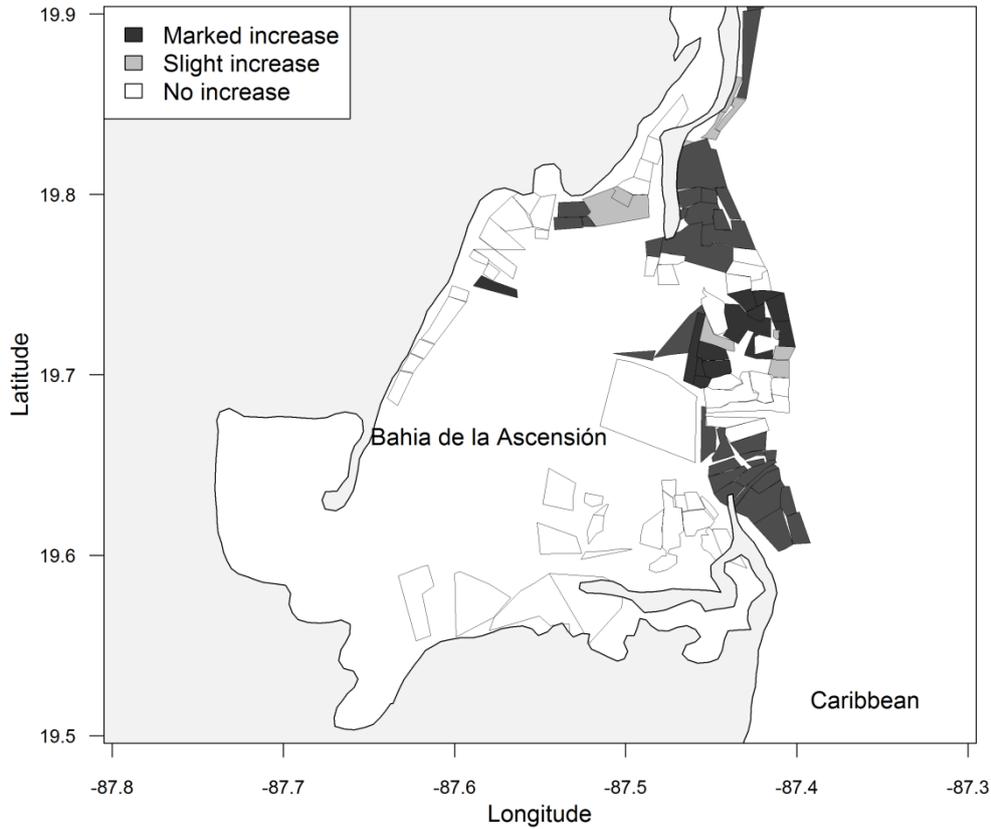


Figure 7-3). Only three of the locations situated on the eastern edge of the bay did not show this pattern. A common feature of these three locations was that they were all associated with relatively deep inlets (>6 m) linking the inner bay to the offshore reefs. Apart from these three locations all others that did not show marked increases in catch rates during autumn

were located within the bay (

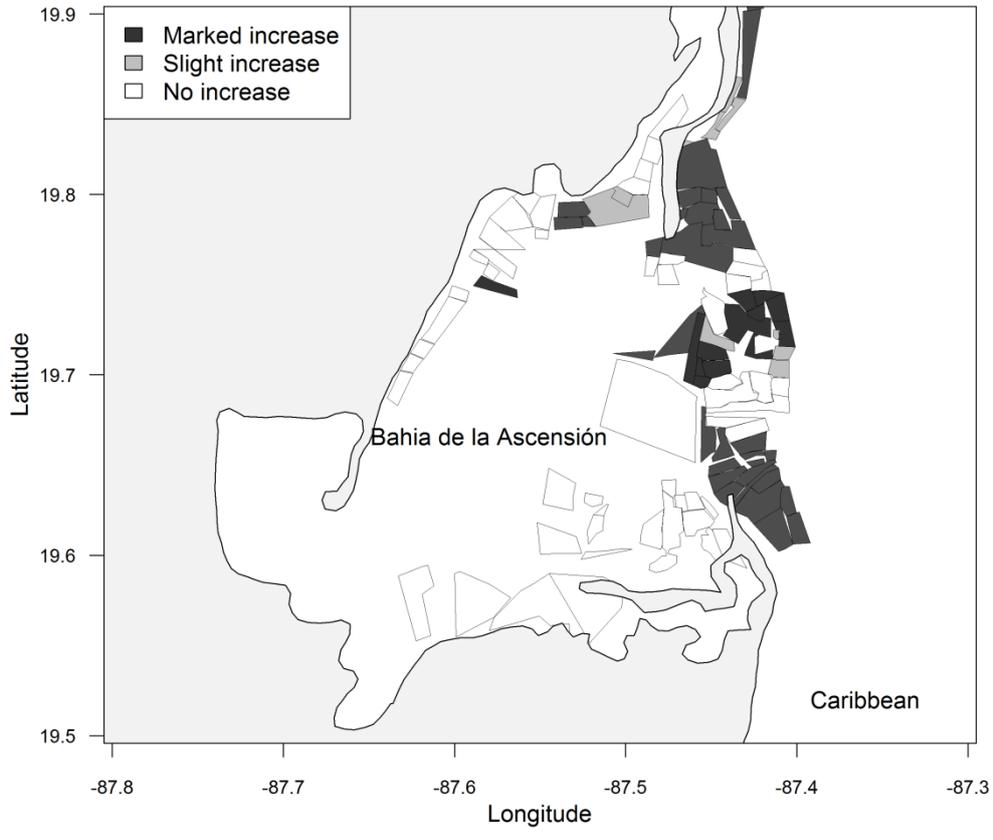


Figure 7-3).

7.3.3 Temporal variation in catch rates

Catch rate trends for each fishing season were described for the whole fishery by pooling together all locations, and the 4th order polynomial accurately replicated this pattern (see

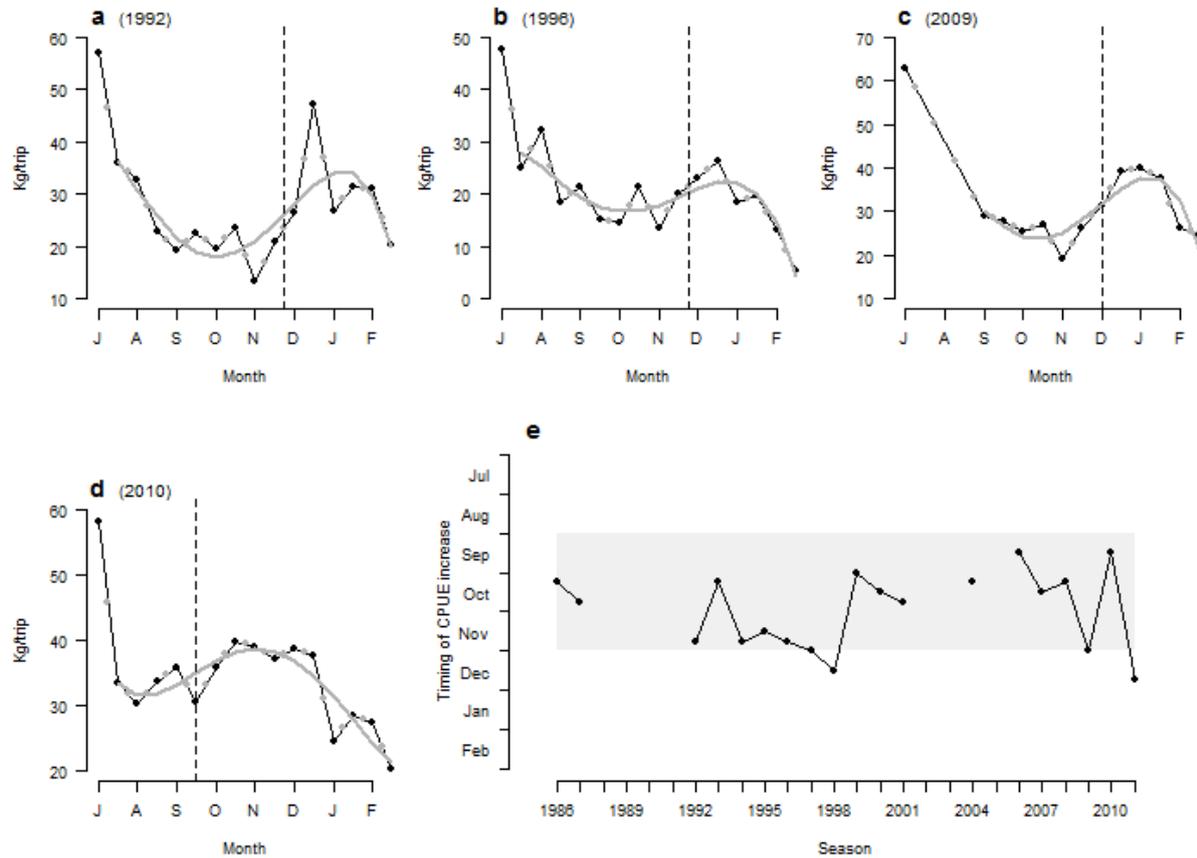


Figure 7-4a-d for examples). All of the 19 years examined displayed some degree of increased catch rate during autumn to early winter and the timing of this event varied between years. The timing of this increase ranged from as early as mid-September in 2006

and 2010 to as late as mid-December in 2006 and 2011 (

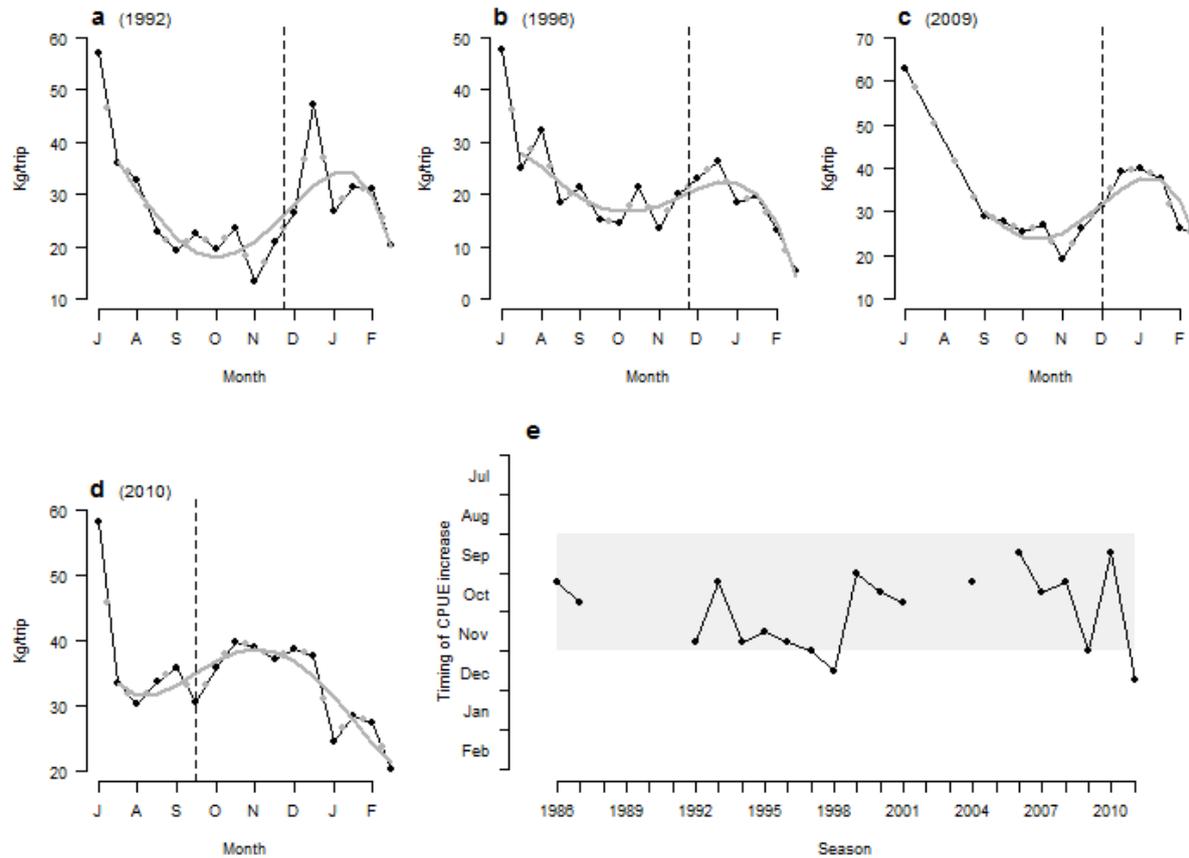


Figure 7-4e). The magnitude of the increase in catch rates also varied markedly between years with increases ranging from only a slight increase of ~20% to catch rates increasing by more than double (e.g. in 2009 catch rates increased from 20 kg/trip in September to 40

kg/trip in December;

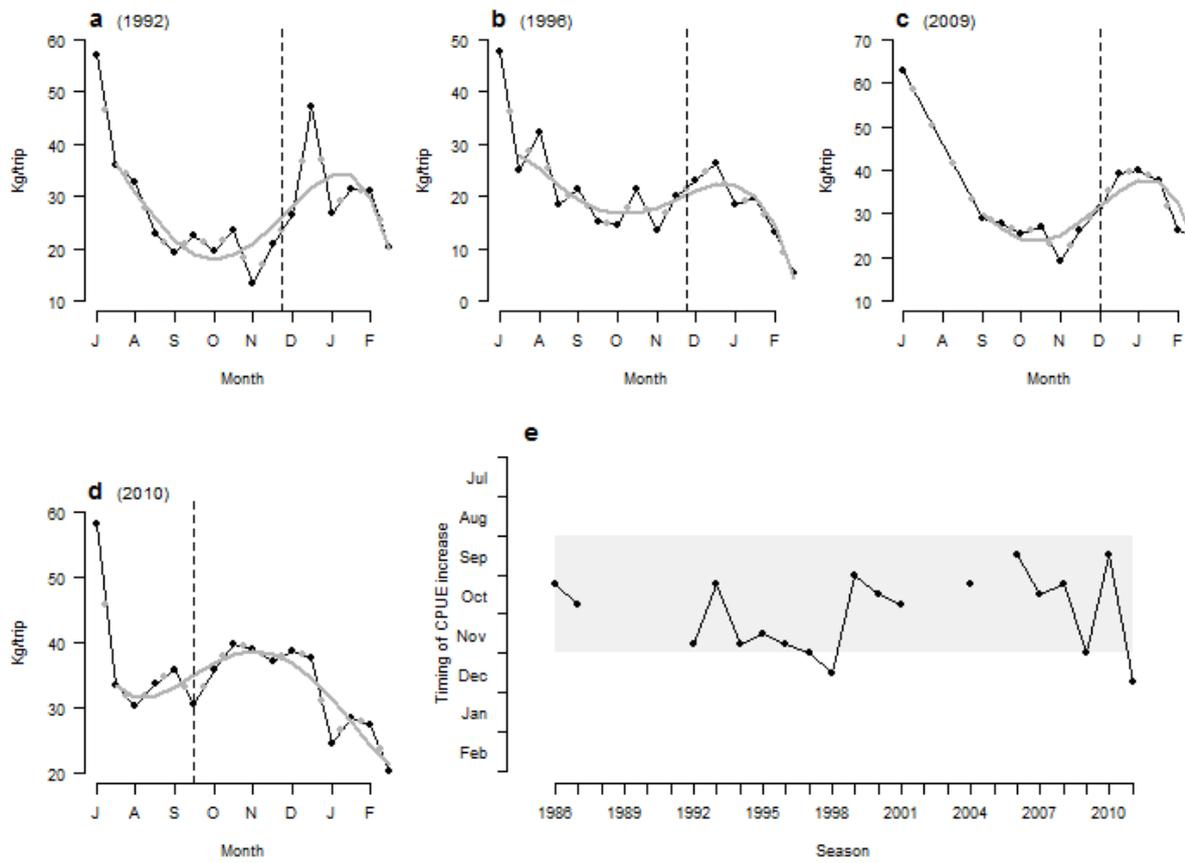


Figure 7-4c).

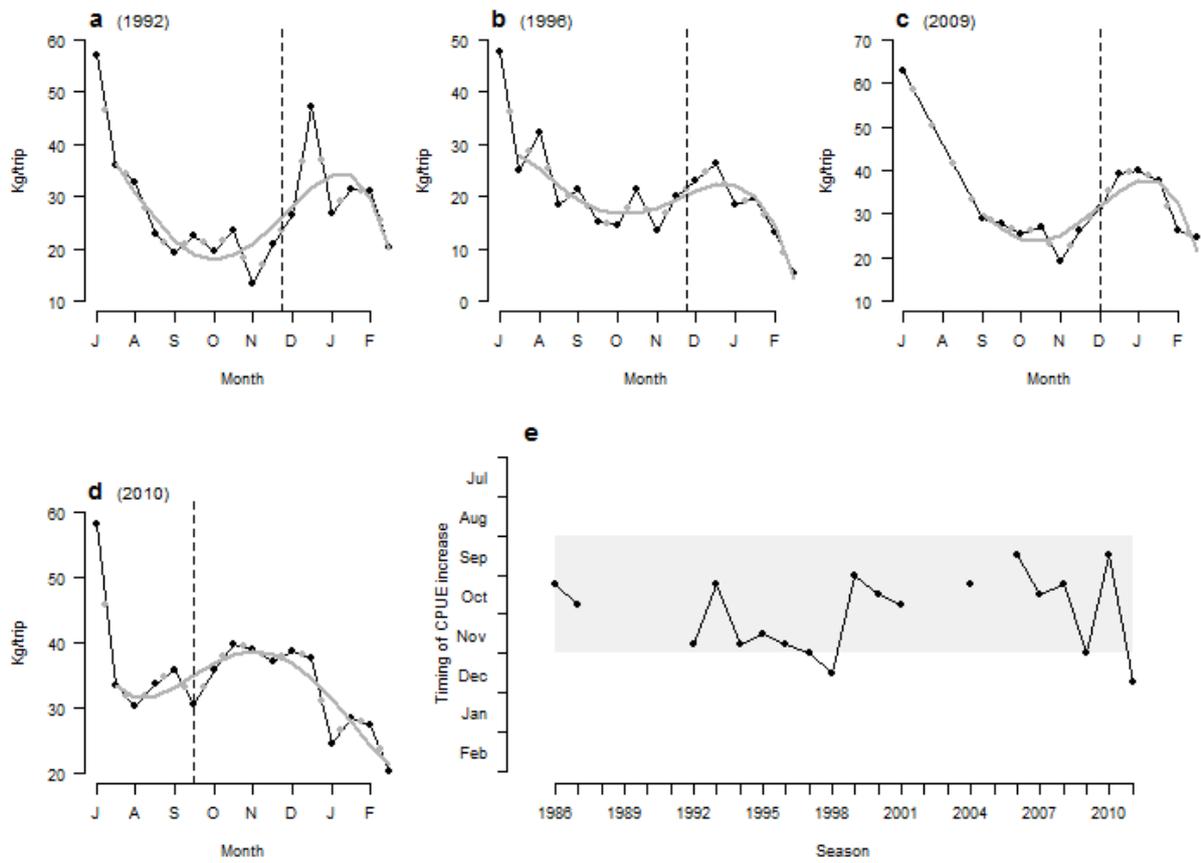


Figure 7-4: Examples of half-monthly catch rates (black points), interpolated quarter-month mid points (grey points) for fishing seasons spanning July to February (a–d) and their associated fitted polynomial models (solid grey line). The vertical dashed lines represent the point of the maximum positive gradient of the polynomial used to assign the mid-point of the increase in catch rates. The resultant mid-point of the timing of when catch rate increases (e) from 1986 to 2011 (black), with the months representing autumn identified by the grey rectangle. Fishing seasons with missing values occurred due to no data being available for those seasons.

7.3.4 Temporal variation in breaching of threshold levels by the environmental measures

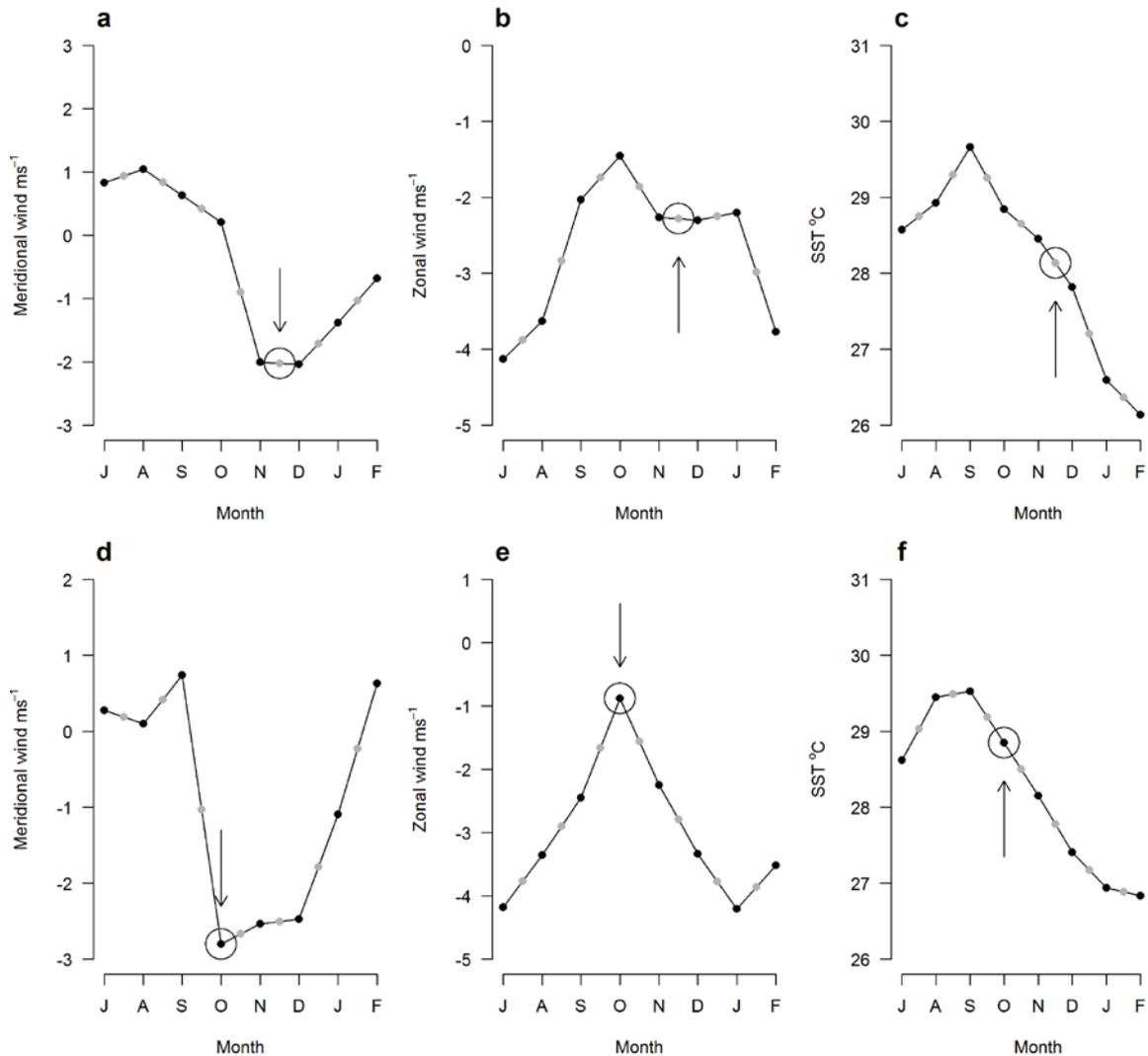


Figure 7-5: Examples of average meridional wind velocities (ms^{-1} , a, d), average zonal wind velocities (ms^{-1} , b, e), and average sea surface temperatures-SST ($^{\circ}\text{C}$, c, f) in two years, 1996 (a - c) and 2011 (d - f) respectively, where monthly values are black points and interpolated half-month are grey points. The circles and arrows identify the timing of the CPUE increase that occurred in the fishery during that specific year

The half-monthly trends in meridional and zonal winds and SSTs each showed similar patterns between the two different years shown in the example, yet these variables were markedly different amongst each other within the same year (e.g. Figure 5). In the two years shown in the example (Figure 7-5), mean half-monthly meridional winds in showed a change from slightly southerly in July, dropping rapidly to be strongly from the north in November and October in 1996 and 2011, respectively (Figure 7-5a, d). In both years meridional winds from the north were weak in every other month of the year. Zonal winds, however, showed a similar yet inverted pattern in both years, with strong easterly winds in July slowly declining

to weak easterly winds in October, before increasing again in strength through until the end of the fishing season (Figure 7-5b, e). Sea surface temperatures (SST) showed a pattern more similar to that of the zonal component of the wind, increasing about one degree over the first two months from July to October before declining to minimum values of 26 and 27° C in 1996 and 2011, respectively (Figure 7-5c, f). In these two examples the timing of the increase in lobster catch rates determined for the fishery occurred just after the marked decline in the meridional component of the wind (Figure 7-5a, d), at or following the minimum period of wind velocity in the zonal component of the wind (Figure 7-5b, e) and along the declining phase of SST between 28 and 29° C (Figure 7-5c, f).

7.3.4.1.1 Relationship between environmental variables and increases in catch rates

Of the three environmental variables used to examine the relationship between their breaching of ATV and the timing of marked increases in catch rates, the meridional wind was the only variable to display a significant linear relationship (

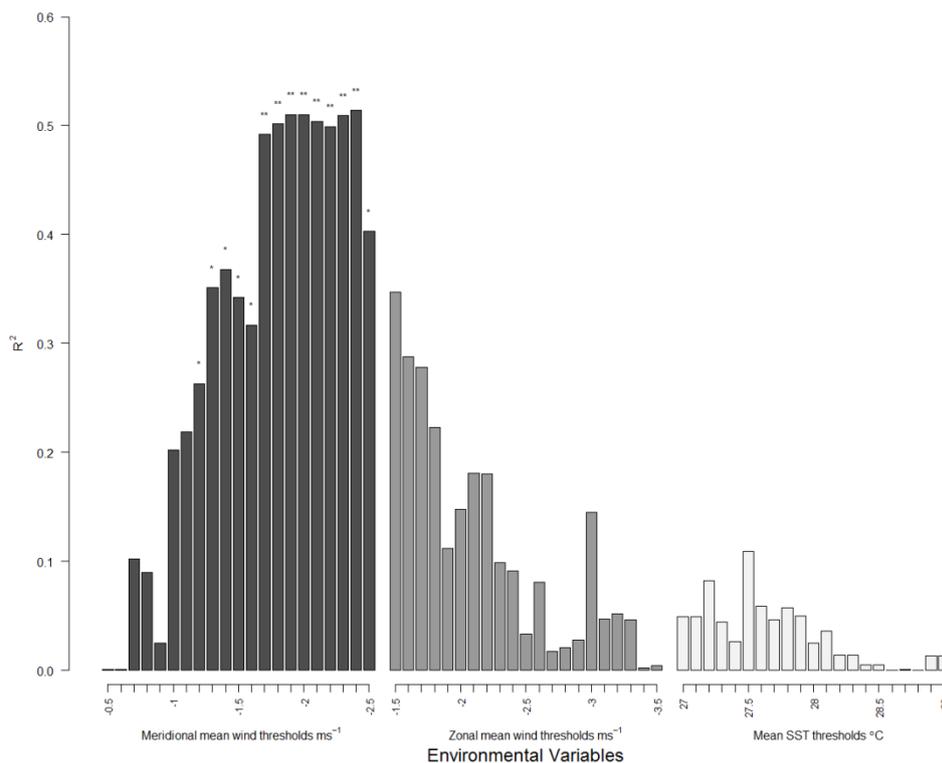


Figure 7-6). As the meridional wind ATV decreased from -0.5 to -2.5 ms^{-1} southwards, the timing of when this value was breached progressively explained a greater proportion of the variation in the timing of increasing catch rates, with a marked increase in R^2 occurring between ATV of -1.6 and -1.7 ms^{-1} , i.e. from an R^2 0.35 to 0.52 (Fig. 6). ATV of -1.7 to -2.4

ms⁻¹ presented the highest correlations, as they had little differences in the R^2 values (0.51 and 0.53), and showed a significant relationship (P -values = 0.0015–0.0019, $df=14$) between the timing of the ATV being breached and the timing of catch rate increments occurring (e.g. in December 2009, 30 kg per trip, see

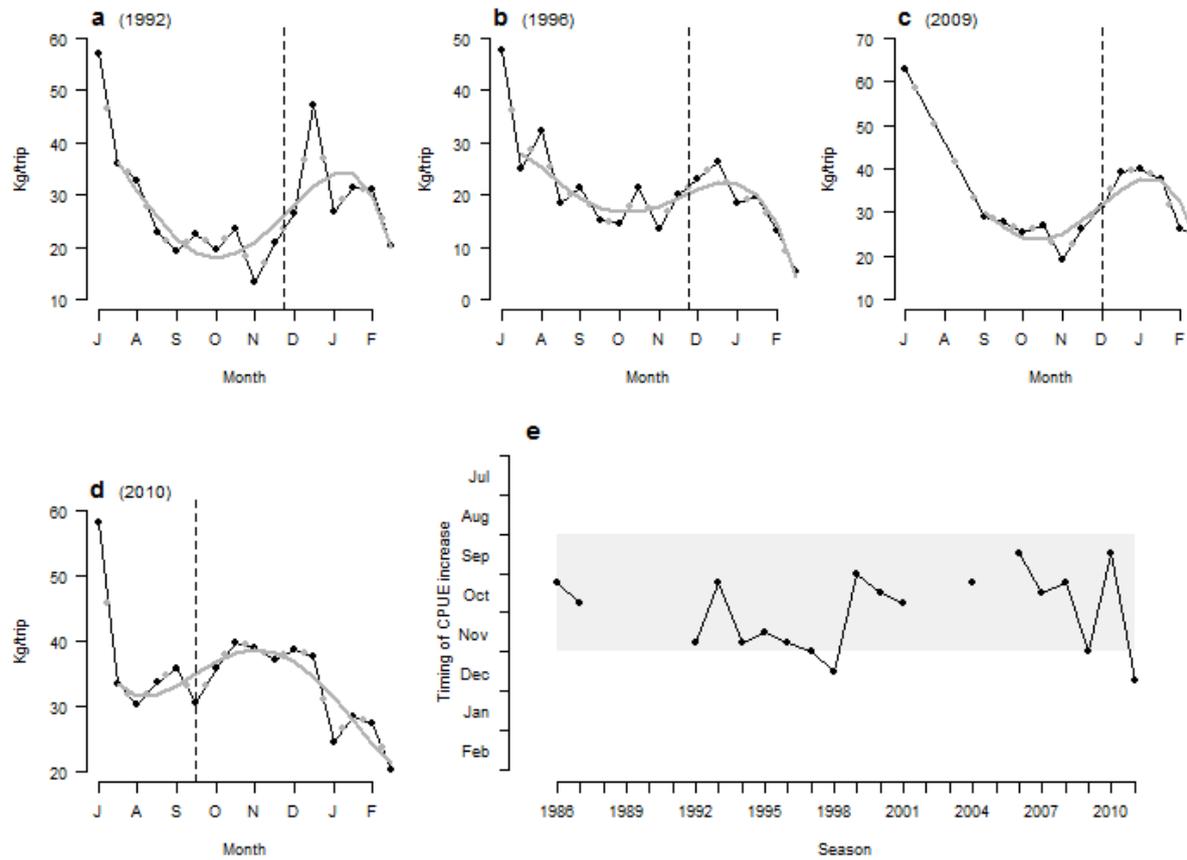


Figure 7-4c).

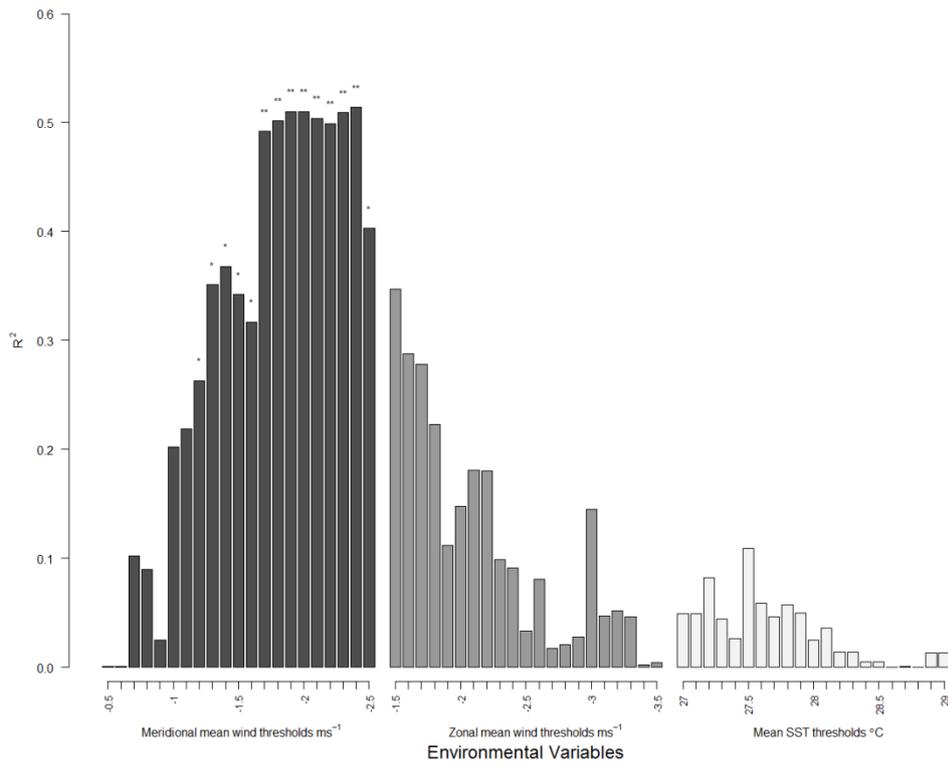
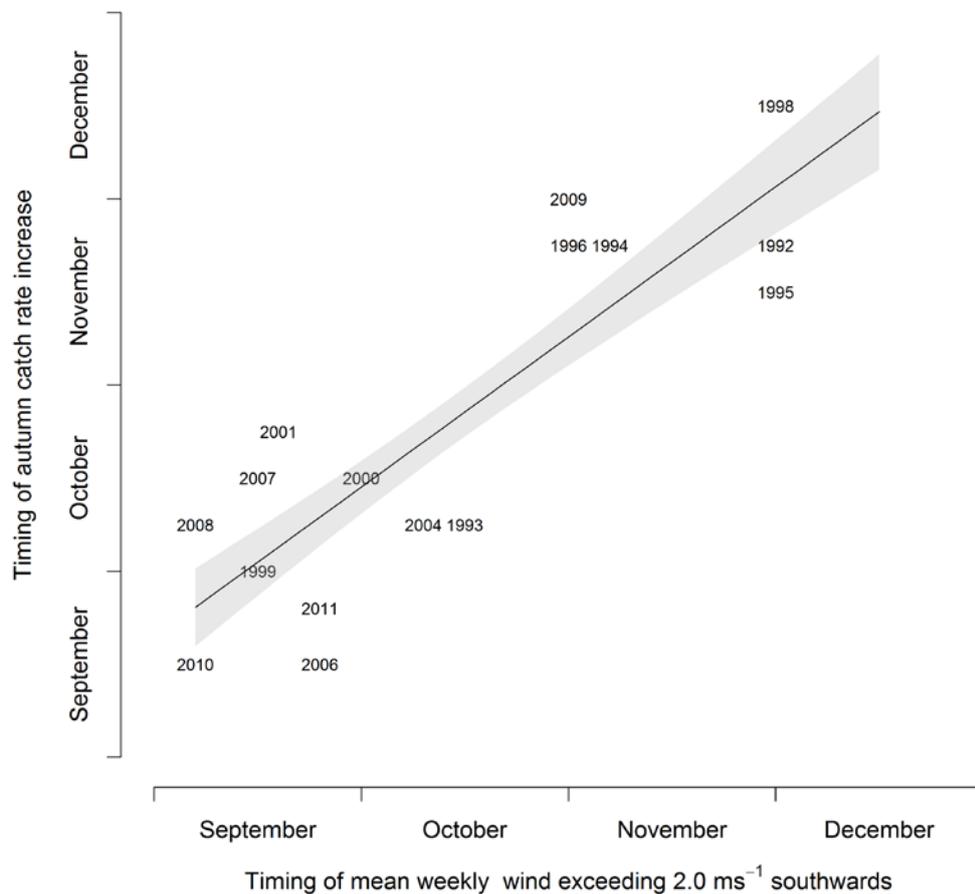
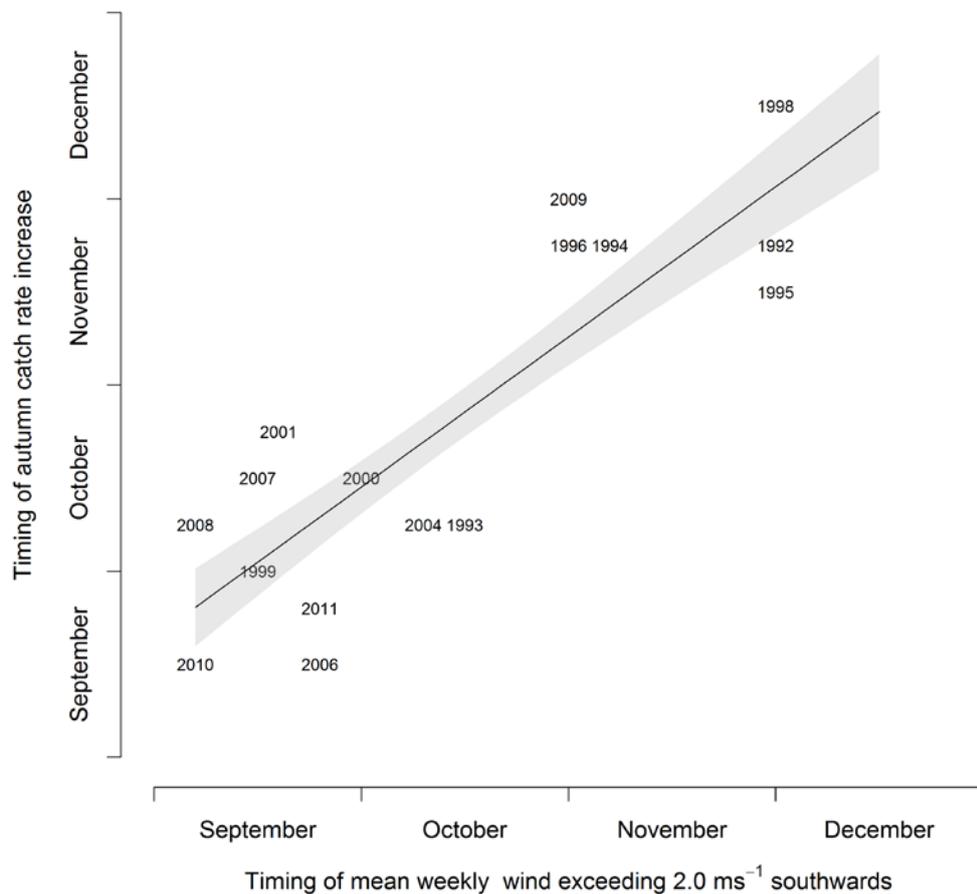


Figure 7-6: Coefficient of determination (R^2) between the timing of when environmental variables breached their respective threshold levels and the timing of when commercial catch rates in Bahía de la Ascensión increased markedly during the autumn period of the fishery. The significance level of the various relationships are shown above each bar with blank, * and ** each denoting $P > 0.05$, $P < 0.05$ and $P < 0.01$, respectively

The mid-point ATV of meridional winds of 2.0 ms^{-1} was chosen to further examine its relationship with catch rate increments in BA (



), since the timing of all threshold values between -1.7 and -2.4 ms^{-1} were very similar as has been previously explained. The slope and intercept of the linear relationship between these two measures did not differ significantly from one and zero respectively (both $P > 0.05$), indicating that the timing of meridional winds reaching -2.0 ms^{-1} was statistically very similar to the timing of catch rate increase in this fishery. Although the intercept was not statistically different from zero, the average elevation on the y-axis of the linear relationship above a bisecting line represented a period of $\sim \frac{1}{2}$ month suggesting that, on average, catch rates increased by this time lag ($\sim \frac{1}{2}$ month) after northerly winds reached an ATV of 2.0 ms^{-1} (



). The linear model between the timing when meridional winds increased above 2.0 ms⁻¹ southwards, and the timing when commercial catch rates in Bahía de la Ascensión increased markedly presented an $R^2 = 0.526$, where the intercept was Estimate = 1.35, SE = 2.71, T value = 0.50, $P = 0.63$, and the meridional wind was Estimate = 0.89, SE = 0.25, T value = 3.50, $P = 0.0035$, $df = 14$.

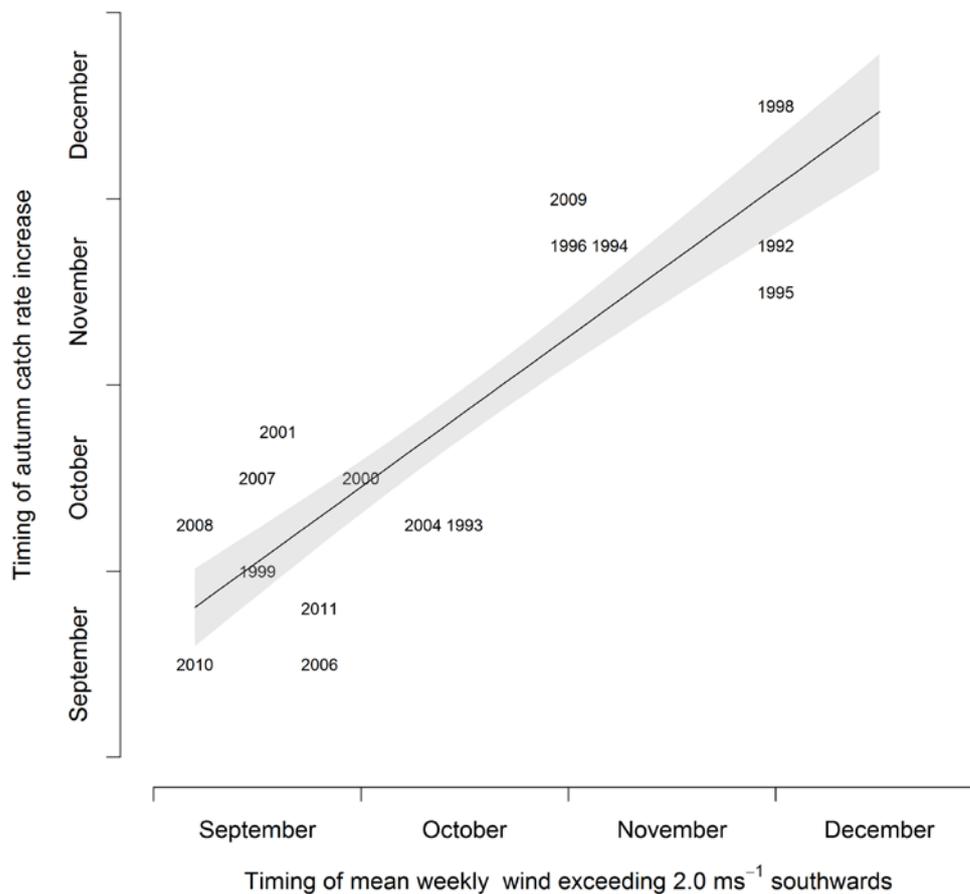


Figure 7-7: Linear relationship (solid line) \pm 1 SE (grey area) between the timing of when Meridional winds breached a threshold wind speed of -2.0 ms^{-1} southwards (half-monthly intervals) and the timing of when commercial catch rates in Bahía de la Ascensión increased markedly during the autumn-winter period of the fishery (quarter-monthly intervals). Each fishing season is identified by the year when the season started, i.e. the July 2000-February 2001 season is identified as 2000

Although the estimated day when zonal winds breached ATVs failed to explain a significant proportion of the variation in the timing of when catch rates increased ($P > 0.05$), this relationship did show an improving trend with larger ATVs (e.g. from -2.5 to -1.5 ms^{-1} westwards), with a threshold of -1.5 ms^{-1} representing periods when the easterly wind was at its weakest. The timing of these light easterly winds explained almost 30% of the variation in the timing of catch rate increases (Fig. 6). The timing when sea surface temperatures breached the range of threshold levels had a very poor relationship with the timing of catch

rate increases, with no threshold level explaining more than 10% of the variation in catch rate increases.

7.4 Discussion

In the Mexican Caribbean and the nearby Cuban *P. argus* fishery, catch patterns follow similar general trends showing two evident peaks, one at the start of the fishing season and the second during the autumn period from October to December (González-Cano 1991, Lozano-Álvarez et al. 1991, Puga et al. 1996, Sosa-Cordero et al. 1999, González-Yáñez et al. 2006). The first peak can be explained by growth and accumulation of lobsters after 4 months of closure (Lozano-Álvarez et al. 1991). The second peak has been ascribed to the effect of Nortes (García et al. 1991) and the present study has shown that the autumnal increase in catch rates in Bahía de la Ascensión is related with northerly winds speed reaching a 15-day average threshold value (ATV) of $\sim 2 \text{ ms}^{-1}$.

When the northerly ATV was $>1.7 \text{ ms}^{-1}$, there was a significant linear relationship with the timing of an autumnal increase in CPUE, i.e. local lobster abundance. By contrast, ATV in easterly winds and sea surface temperature (SST) were less significantly related to the timing of the increase in CPUE. A sharp decline in water temperature over several days due to autumnal cold fronts has previously been linked to migrations in *P. argus* (e.g. Herrnkind & Kanciruk 1978, Kanciruk & Herrnkind 1978, García et al., 1991, Bertelsen 2013), but such a relationship was not evident in the datasets examined in this study. However, this could be an artefact of the interpolation to obtain SST daily values from monthly data and of the 15-day CPUE averages used to estimate threshold values. In our study area, water temperatures have generally reached their peak during autumn and thereafter start to decline, and this dominant change in water temperature is not associated with Nortes. However, an examination of four years of water temperature and wind speed data collected on a fine temporal scale (daily) in Puerto Morelos ($\sim 130 \text{ km}$ north of BA) by UNAM (data not shown) revealed that sharp drops of 2° to 3°C in water temperature do occur for one to three days following the strong northerly winds. Therefore not surprising that in this study we found no relationship between the 15-day averaged SST and catch rate increases, which are indicative of movements and migration. The analysis of the BA fishery for the 1985 to 2012 period clearly shows that Nortes have historically induced an evident increase in catch rates/abundance when 15 day-average wind strength reaches $\sim 2.0 \text{ m s}^{-1}$ in a southbound direction.

In addition to sudden drops in water temperature, other factors that may induce movements in spiny lobsters include increased water turbulence, turbidity, and swell, all of which are also associated with strong Nortes (Kanciruk & Herrnkind 1978, Herrnkind 1980), and changes in salinity (Rao & Kathirvel 1971, Morgan 1974), which are not necessarily associated with Nortes. For example, at Puerto Morelos, monthly average values of significant wave heights are higher during the winter relative to the rest of the year, reflecting the influence of waves generated by Nortes (Coronado et al. 2007). Large swells are correlated with greater catches of other spiny lobsters (*P. cygnus*: Srisurichan et al. 2005; *P. ornatus*: Tewfik 2014). Estimates of the flow of water in and out of BA indicate a persistent net outflow from the bay to the adjacent shelf, suggesting an intense exchange across the inlets in the bay's mouth (Medina-Gómez et al. in press). However, water transport is modulated by the combined effect of tides and wind stress. In particular, currents in BA characteristically exhibit motions parallel to that of the winds acting in the zone; that is, winds from the north and northwest would tend to push the water out of the bay (in an easterly direction) and alongshore (in a southerly direction) (Medina 2011). In addition, due to orientation of the coast and Eckman transport, winds from the north would cause downwelling of coastal waters, potentially transporting suspended particles to greater depths. Due to groundwater discharge and the absence of marsh filtration in SKBR, the bay is more nutrient enriched than the adjacent shelf, especially after the rainy season (Medina 2011). Therefore, it is reasonable to assume that water turbidity in the bay and the adjacent shelf would increase after the passage of a strong Norte. Although turbidity was not measured in this study, it is well known that activity of lobsters increases during periods of reduced visibility, e.g. during the dark lunar phases (*P. argus*: Sutcliffe 1956, Bertelsen 2013; *P. cygnus*: Morgan 1974, Srisurichan et al. 2005) and when turbidity increases (*P. argus*: Herrnkind et al. 1973, Lozano-Álvarez et al. 1994; *Homarus gammarus*: Smith et al. 1999). Turbid water may allow lobsters to move greater distances in the search for food and possibly promote long distance migrations of Subadults and adults.

In SW Cuba, where casitas (locally called “pesqueros”) are also extensively used to fish for *P. argus* lobsters, the CPUE follows a similar monthly trend as in BA, but the autumnal increases in CPUE are proportionally higher than in BA (González-Yáñez et al. 2006). However, upon arrival of the first Nortes, Cuban fishers deploy “jaulones”, rectangular traps (usually 10 units in each long rope) joined by pieces of 40 m-long nets designed to take advantage of migrating lobsters, so that from October to February 70% of the catch is

obtained with jaulones (Puga et al. 1996). In contrast, the fishery for *P. argus* in BA depends exclusively on casitas throughout the fishing season, so the autumnal increase in catch rates reflects an increased abundance of legal-size lobsters recruiting into casitas.

The autumn peaks in catch rates were more evident in the eastern campos close to the reef. This is an indication of increased abundance of legal-sized lobsters recruiting into the areas subject to fishing, and it is reasonable to say that a considerable proportion of these lobsters are present due to migration pulses (Lozano-Álvarez et al. 1991, 1993, Ley-Cooper et al. 2013). Tagged lobsters have been recorded to move from BA to Bahía del Espíritu Santo (BES) and the recapture times suggest that these lobsters came in during one such redistribution event (Lozano-Álvarez et al. 1991; Ley-Cooper et al. 2014). Exploratory fishing with traps in the deeper, unfished offshore area showed that lobsters in this area were mostly adults with a mean size significantly larger than the size of lobsters dwelling within the bay (Lozano-Álvarez et al. 1993). However, lobsters from the unfished area were significantly smaller in the winter than in the summer, especially after the passage of severe Nortes, suggesting that Nortes trigger migratory pulses of Subadult and young adult lobsters from the shallow bay towards the deeper unfished area (Lozano-Álvarez et al. 1993). Offshore movements of *P. argus* associated with cold fronts have also been documented in other parts of the Caribbean and Florida (Herrnkind 1980). Changes in salinity within the shallow BA may further contribute to these movements. Due to the karstic geology of the Yucatan peninsula, there is a significant input from submerged groundwater discharge along the southwestern margin of BA resulting in an estuarine, horizontal salinity gradient perpendicular to the mouth of the bay (Medina-Gómez et al. in press). At the end of the rainy season (i.e. October), salinities in BA range from 1 to 33.9‰ with the highest values occurring towards the mouth of the bay (Medina-Gómez et al. in press). As *P. argus* lobsters do not tolerate salinities below 19‰ (Witham et al. 1968), a synergistic effect of a sharp drop in water temperature during a strong Norte in combination with the salinity gradient at the end of the rainy season may increase movement of lobsters from the inner bay towards the mouth of the bay. During their migration from shallow bay areas towards deeper areas, some of these lobsters may occupy casitas in the easternmost campos, where salinity is less affected by groundwater discharge (see Medina-Gómez et al. in press).

On the other hand, large adult lobsters are also commonly found in the bay and shallow adjacent reefs, suggesting that some lobsters return to inshore habitats after their ontogenetic migration to deeper habitats (Lozano-Álvarez et al. 1993). Indeed, several lobsters that were

tagged and released in sites over 20 m in depth off BES were recaptured within the bay (Ley-Cooper et al. 2014), indicating that large lobsters can move from the unfished areas into the fishing grounds in the bay. These latter studies suggest that, after breeding in offshore areas of the deeper shelf, some adult lobsters probably return to the bays to forage, as there are plenty of food resources in the shallow bay habitats (Vidal & Basurto 2003). In Cuba and Florida, large *P. argus* lobsters have also been recorded to move from deeper areas into shallow back-reef areas to forage (Buesa Más 1970, Cox et al. 1997, Bertelsen 2013) and in other marine species, adults commonly migrate into estuaries and shallow lagoons to take advantage of rich nutrients (Dingle 1980). Therefore, legal size lobsters possibly recruit to the eastern campos in BA after the passage of strong Nortes due to induced movements of smaller lobsters coming from the inner, western areas of the bay, as well as of larger lobsters coming from deeper offshore areas.

Although marked changes in distribution and abundance of *P. argus* lobsters during the autumn have been reported in other locations such as Florida and the Bahamas (Herrnkind et al. 1973, Kanciruk & Herrnkind 1978), Cuba (García et al. 1991, González-Yáñez et al. 2006) and Isla Mujeres, Mexico (González-Cano 1991), the variability of the timing of increase in catch rates in BA from one year to the next could also be explained by changes in abundance due to variability in natural mortality, growth rates, and reproductive migrations towards the offshore areas (Acosta 1999; Ríos-Lara et al. 2007; Briones-Fourzán & Lozano-Álvarez 2013). However, considering the high levels of exploitation which occur in the SKBR, where most legal lobsters are fished out when available (Lozano Alvarez et al. 1991, 1993; Ley-Cooper et al. 2013), our results suggest that it is the environmental effects associated with Nortes which most likely affect distribution and abundance, and hence catch rates, of *P. argus* lobsters during the autumn period in BA.

It is possible that increased lobster catch related to the onset of Nortes may also be affected by human behaviour associated to the local fisheries dynamics. Yet the correlation between catch rate increments and Nortes suggests that, catch rates increase after winds reached a 15 day average threshold of 2.0 ms^{-1} (see Fig. 7). The spatial variations in catch rates are clearly affected by lobster availability, but also by unfavourable fishing conditions and water turbidity in the shallow bay after the passage of a strong Norte which result in a 5 to 15 day non-fishing period. The latter would enable lobsters to move and aggregate in casitas close to the reef when in the search for food and refuge.

This study evidences that the population dynamics of spiny lobsters may be significantly altered by the species behavioural responses to environmental changes (e.g. Herrnkind 1980, Puga et al. 2013). Since catch rates of spiny lobsters also vary in response to changes in factors such as salinity, moon phases, and ocean swell (Herrnkind et al. 1973; García et al. 1991; Ziegler et al. 2003; Srisurichan et al. 2005; Phillips et al. 2013; Puga et al. 2013), future studies in BA should also consider examining these factors outside of the Nortes season, and probably include wave height and direction to better test the assumption that fishing effort is not changing spatially and temporally.

8 The Chakay and MSC Eco-labelling initiatives in the Sian Ka'an and Banco Chinchorro Biosphere Reserves, Mexico

Many segments of this sections are as published in (Ley-Cooper 2010): Developing Sustainability Principles and Criteria for Management and Eco-labelling in the Sian Ka'an and Banco Chinchorro Biosphere Reserves, Mexico. Proceedings of the 63rd Gulf and Caribbean Fisheries Institute, San Juan, Puerto Rico.

8.1 Research Setting and method

8.1.1 Rationale of the Study

In fisheries a stakeholder is a person involved in the management, the marine environment, or the fishing activity, who could also play a role in the development and implementation of policy instruments (Gray & Harchard 2008, Freeman 2010, Pérez-Ramírez et al. 2012a, Mackinson et al. 2011). In the case of the Chakay and MSC ecolabelling initiatives in BC and SK (Ley-Cooper 2010, MRAG-Americas 2012, Ward & Phillips 2013), stakeholders have been described in detail in sections 1.6 of this thesis, and range from the fisher cooperatives to the final consumer. They include industry and middlemen along the commercial supply chain, to the managers comprising environmental and fishing government authorities, as well as research institutions, NGO's and the general public interested in the sustainability of *P. argus* lobster. Diverse stakeholders have different objectives, interests and preferences as to how ecolabelling initiatives should be conducted (Ramirez et al 2012). Understanding their behaviour, perceptions and influence from a socio-anthropological stand point is fundamental (Origlio et al. 2014).

8.1.2 In depth face to face interviews

The perceptions of stakeholders regarding the Chakay to the MSC certification ecolabelling process and its effects were acquired by in-depth, face-to-face, semi-structured interviews conducted in 2010 and 2012, when Chakay initiative was already in place and during the MSC pre-assessment process (Chafee 2008, Ley-Cooper 2010). The interviews were conducted before after the fishery had been certified in 2012 (MRAG-Americas 2012, Origlio et al. 2014). Stakeholders involved in the Chakay and MSC certification process who were interviewed, included:

a) 10 fishers and the three members of the administrative council (President, Secretariat and Treasurer) of each of the six cooperatives which hold fishing rights in SK and BC (see

sections 1.6.3, 1.6.4 and 1.6.5); b) CONANP management authorities from both BC and SK Biosphere Reserves including Director, Subdirector and 2-3 park rangers; c) CONAPESCA fisheries management authorities including Subdelegación de Pesca, two technicians, and two field operators; d) members from Consejo Estatal de Pesca including leaders from Federación de Sociedades Cooperativas de Quintana Roo, and fishing industry processors and middlemen; e) members of academic research institutes (UNAM, ECOSUR, and CINVESTAV) f) and government authorities from research agencies (INAPESCA, CONABIO); g) members of NGO's including: RAZONATURA, COBI, WWF, TNC, Amigos de Sian Ka'an, all of them related and involved with these fisheries in some way or another.

At the beginning of the interview, stakeholders were informed about the purpose of the research project and asked for permission to take notes, record and film during the interview and to use information for research purposes. The notes were digitalized and information was shared with stakeholders at different stages, in cooperative assemblies, or made public during the MSC evaluation meetings. In this type of interview, to achieve validity and reliability, all stakeholders from the same sector were asked the same questions (Barriball & While 1994). To motivate respondents' participation, the interviewer(s) addressed the fisher's general assembly, explaining the general and specific objectives of this study. Similar to previous studies (Ley-Cooper 2010, Jain & Garderet 2011, Pérez-Ramírez et al. 2012a, Origlio et al. 2014), the interviews were organized around thematic areas, such as a) history of the fishery, b) the impact of Chakay-Integradora enterprise project, c) participation of organizations/institutions, d) market and financial aspects, socio-economics linked to sustainability, d) benefits obtained after implementing ecolabelling initiatives, and d) challenges of the fishery management for achieving sustainability.

The interviews lasted between `thirty minutes to an hour depending on the person who was interviewed. The answers were coded and compared using methods described by Origlio (2007) based on theory of anthropological semiotics. The general concept is that deep hermeneutics structures itself across three sequenced levels of analysis: 1) the socio-historical level, 2) the discursive level, and 3) the interpretive/re-interpretive level. The *socio-historical* level, which constitutes the first step of research, aims to reconstruct the social and historical conditions of production, circulation and reception (we must bear in mind that deep hermeneutics was originally applied to traditional media studies); the *discursive* is an intermediate level of analysis where a closer observation of the text is required; and finally,

the third level, the *interpretive/re-interpretive*, which is the “deepest”, consists of the operations of “creative construction of a possible meaning” (Thompson 1993). The active role of the researcher in the generation of plausible interpretations of a specific text (or phenomenon) inscribes his or her subjectivity in the process of construction of reality sustained on the implicit recognition of a high level “reading competence” of the researcher. His knowledge of the cultural system in which the phenomenon takes place (or the text is produced, circulates or is received) is what validates his or her interpretation. If a certain authority derived from experience and knowledge can be attributed to researchers, the risk of subjective interpretations also has to be considered in the results (Origlio 2007).

8.2 The Chakay -Integradora enterprise project:

The purpose behind the Chakay national trademark (IMPI 2009), was that of developing a successful eco-labelling system that would recognize and usher the six fisher cooperatives with exclusive concession rights, to fish in BC and SK with more sustainable practices (Ley-Cooper & Quintanar-Guadarrama 2010). When the fishery stakeholders were faced with developing a framework for the Chakay project in the BC and SK Biosphere Reserves, there was a strong push from the fishing communities to focus on adding value and differentiating their local product in the market, from other lobsters caught and sold illegally. Since there was a need to generate additional income and create new jobs in these fisher communities, following a fair trade system (Liu 2010) seemed the most appropriate means to fulfil these needs, without having to increase fishing effort.

Leveraging economic benefits linked to the objective of enhancing sustainable practices was a viable strategy for engaging stakeholders in the ecolabelling process while simultaneously improving governance. This was achieved to great effect in BC when fishing gear was exchanged and fishing methods transformed from catching lobsters with hooks and selling them as tails, to a system where snare loops for catching lobsters alive were used exclusively (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009). This change in fishing gear implied an increase in value, as landing volumes were triplicated simply by not discarding lobster heads, thus transforming total catch volumes per season by a $\geq 3:1$ relationship from $\approx 20t$ (TW) to $\approx 65t$ (WW), while effectively increasing the income due to the price weight relationship of \$38 USD per kg of tails (TW) to \$20 USD per Kg of live lobsters (WW), resulting in 30% added value (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009)..

Local fishers' engagement with the "Chakay" eco-labelling scheme has helped catalyse several conservation initiatives within the MPAS's, under the premise that it has effectively generated an added value in the chain of custody, especially for the BC cooperatives. However, experience has also revealed that unless there are penalties for fishers who engage in unsustainable practices, the project's success in reaching the aims and goals may not be accomplished. Normally legal enforcement is carried out by the environmental (CONANP, PROFEPA), and Fishing (CONAPESCA) authorities (INE-SEMARNAP 2000, CONANP 2007), yet penalties such as those established in the Chakay's eco-labels "rules of use" (IMPI 2009), are an additional legal instrument ensuring compliance to environmental and fishery regulations, within a legal framework which should be met when working within the BC and SK MPA's. The effectiveness of implementation of legal tools is significantly stronger when cooperatives internally agree to incorporating certain "rules of use" into their own cooperative principles for commercialization, and decide to do so by an assembly agreement (Velez 2014). In the absence of governmental authorities as often occurs in remote fishing communities, the fishing cooperative's self-governed administrative council/assemblies represent the organism demanding most respect from associated fishers.

The Chakay ecolabelling scheme represents an exemplary international case study for financing fishery change (Jain & Garderet 2011), and both the SK and BC have recently obtained the Marine Stewardship Council (MSC) certificate of sustainability (MRAG-Americas 2012, 2013). However, the long term goals and aims of both MSC and Chakay ecolabelling schemes may be destined to failure in their attempt to achieve sustainability, if they exclusively dedicate their actions and controls to regulating the local fishing cooperatives, as management of a meta-population such as *P. argus* in the MBRS cannot possibly only remain local (Herrnkind 1980, Sissenwine & Shepherd 1987, Caddy & Seijo 2005, Seijo 2007, Ehrhardt et al. 2010a).

The SK and BC *P. argus* populations are semi-open (see discussion 9.3.1.1.1), and fishery characteristics are subject to regional dynamics of the species comprising the MBRS meta-populations (see discussion in section 9.1 and 9.3)(González-Cano et al. 2001, Naro-Maciél et al. 2011, Truelove et al. 2011, Truelove et al. 2014, Truelove et al. 2015). Pueruli recruitment greatly depends on source populations from elsewhere in the Caribbean (Briones-Fourzán 1994, Briones-Fourzán et al. 2008, Truelove et al. 2015) and likewise adult coastal migration connectivity patterns are still not well defined (González-Cano 1991, Bertelsen 2013, Ley-Cooper et al. 2014). This means that ecolabelling schemes must consider ways to

influence behaviour beyond that of local stakeholders who actively participate in the BC and SK MPA's. Plans for action should incite sustainability in other fisheries both southwards and northwards in the MBRS, especially those which are potentially sourcing larvae and pueruli recruitment to BC and SK (Truelove et al. 2014). Sustainability principles and criteria should appeal to the general public and market places beyond the local BC and SK boundaries. Stakeholders who participate at any level of the commercial chain with these lobsters should somehow engage with the ecolabelling schemes and capitalize on these initiatives, by making commercial use of the ecolabels to gain additional value (Ley-Cooper & Quintanar-Guadarrama 2010, Agnew et al. 2013).

Successful implementation of ecolabelling requires making economic benefits more tangible, which could be achieved at all levels in the chain of custody. Capitalizing a 20-30% added value has been achieved when lobsters were traded directly between cooperatives and final consumers (i.e. restaurants and hotels) which were willing to engage with the ecolabelling's commercial scheme under a fair trade system (Liu 2010). This has enabled prices to increase up to 33% on dock prices (Ley-Cooper 2009). A larger group of community/stakeholders should attain access to these benefits by participating in the certified chain of custody, or in activities linked to these fisheries beyond the MPA's boundaries. This would encourage enterprises that currently provide outsourcing services to these fisheries to actively promote ecolabelling and sustainability, while possibly creating more jobs and revenue for the entire commercial chain, hence promoting sustainability at all levels.

Trial sales and trading experiences with the enterprise Integradora (IPQRoo) has shown that fishers participating at higher levels in the chain of custody who are able to attain true added value, engage better with the principles of overarching eco-labelling schemes (Jain & Garderet 2011),(Pérez-Ramírez et al. 2012b, Pérez-Ramírez et al. 2015). The board of directors at IPQRoo progressively acknowledge the value of tracing lobster from the boat to the plate, when carrying the flag of a sustainable/quality product, yet information and benefit does not necessary filter down to all fishers associated with the cooperatives(Ley-Cooper 2009). Catalysing the development of a successful and economically viable sustainable fishery business, at all levels of the commercial chain is a long and expensive process, but worth attempting when changes in fisheries are being financed (Jain & Garderet 2011). The MSC and Chakay ecolabels are not yet the most effective tool for marketing purposes in Mexico (Pérez-Ramírez et al. 2015), but certainly a way to endorse fishing communities that

are working towards sustainability, and a means of increasing international reputation, image and community standing, which are also valued attributes (Pérez-Ramírez et al. 2012b).

8.3 Working capital for financing changes in fisheries: attaining sustainability along the supply chain.

In many developing countries such as Mexico, and specifically in the BC and SK MPA's, the fishing cooperatives operate at the bottom of the supply chain (Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011), and middlemen who supply the final consumers and the tourist industry benefit from the fishers' shortage of working capital funds for basic fishing operations. Most cooperatives lack financial tools and resources to withstand the closed fishing season.

Many middlemen are able to supply monetary loans to cooperatives at very high interest rates (>20% per annum), which are regularly provided for fishing operations as working capital during the closed season, or just before the start of the fishing season, to guarantee their slot of lobsters which are yet to be harvested. This business scheme is feasible and profitable for middlemen as they have access to sophisticated transport, storage, and freezing facilities which most cooperatives lack. Furthermore, cooperatives do not have the capacity to withstand the credit required by hotels and restaurants which tend to delay payments for up to three months after reception of the product.

Likewise, hotels and restaurants can potentially pay up to 50% more on prices with regards to dock prices of \$20/kg USD for whole lobsters, as they in turn can resell lobsters to customers for up to \$100/kg USD, when served on the plate. Fishers are usually unable to withstand the three month delay in credit payment imposed by these hotels and restaurants, as they normally require immediate liquid cash payments to sustain daily operations, and can therefore not sell directly to these potential buyers, even if they have the commercial connections required for business. Lack of storage and processing facilities imply additional outsourcing costs, thus cooperatives also tend not to benefit from market price escalations that occur during the closed season (March to June) when the tourist season is fairly high, and lobster prices climb by up to 30% with respect to the regular season (July to February) prices.

If the BC and SK cooperatives want to improve their participation in ecolabels, and become more profitable by becoming independent from middlemen, they should consider three key factors from a management and business administration perspective: 1) increase storage and transport capacities and facilities, 2) capitalize the 30% difference in prices between the closed season and the regular fishing season, 3) respond to the ever-growing

demand for live lobsters in the market, instead of lobster tails as live lobsters sell for a better price (i.e. \$20 USD /Kg (WW) vs. 38 USD/Kg (TW) in a 3:1 volume proportion. This practice could drive market forces and result in changes with the introduction of new harvesting strategies and techniques. Using market forces to drive change has partially been achieved in BC, by the introduction of snare loops for live lobster catching (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009). It appears that the opportunity to satisfy market based needs, while simultaneously respecting eco-labelling principles, might permit the introduction of further significant changes in management strategies, including new harvest control rules (HCR's) required by MSC for a continued certification (MRAG-Americas 2013). Current market barriers may thus evolve into opportunities for changing bio-economic paradigms; hence optimizing harvest rates, limiting effort and regulating the total catch in order to maximize economic benefits (Ley-Cooper & Chávez 2009, Gardner et al. 2013).

Entry to the SK and BC MPA's is restricted to limited access, and the fishery is controlled by local park authorities (INE-SEMARNAP 2000, CONANP 2007), the less costly solution for storing live lobsters is arguably: a) leaving them untouched directly under casitas in the assigned Campos, which are under surveillance and co-management by the fishing cooperatives and park rangers; or alternatively b) once lobsters have been caught, they can be placed in low cost cages which allow free water flow, such as the so called "chiqueros" constructed with wooden poles and stainless steel fencing wire walls placed inside the coastal water column. These differ from holding tanks kept inland, as no oxygen pumps, electricity or costly infrastructure is required.

Both storing methods have potential advantages and disadvantages such as: a) casitas are open artificial refuges providing no guarantee that lobsters will stay within the same campo when *P. argus* ontogenic habitat shifts and migrating movements occur (see chapter, 0) (Briones-Fourzán & Lozano-Álvarez 2013), similarly natural mortality, growth and weather are features that are likely to affect catch rates and spatial variance of landings (see chapters 4, 0, 6 and 7). b) Cages on the other hand imply feeding expenses and maintenance, where additional mortality may occur because of behaviour changes such as increased cannibalism resulting from captivity and high density conditions, as was observed in the tag loss experiment carried out in holding tanks for this study (see section 5.2.1.1.3).

Leaving the lobsters untouched under casitas clearly implies a different approach to stock management and impact on population dynamics than the use of closed cages which restrict

free movement. Casitas will aggregate lobsters but allow freedom of movement and scarcely cause negative effects on population dynamics (Briones-Fourzán & Lozano-Álvarez 2013, Ley-Cooper et al. 2013). In contrast, holding lobsters in cages where they are confined to a fixed space, restricts movement and is likely to affect natural feeding habits, growth and reproductive behaviour (Briones-Fourzán et al. 2003, de León et al. 2005, Ehrhardt 2008). Regardless of the method preferred, these simple “storing” strategies allow for harvesting lobsters only when prices are at their highest, and would thus increase economic returns, if there happened to be consensus on implementing a Bio-economically backed strategy (Penn et al. 1997, Morgan et al. 2009, Gardner et al. 2013), such as the development and implementation of an input and output-based management system (Penn et al. 2015). For example amongst the cooperatives that operate in these MPA’s, a temporary fishing ban in the autumn period (September-November) could be agreed upon, when “Norte” recruitment peaks occur (see chapter 7) (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014) and prices are at their lowest.

Fishers are seeking support to effectively link into the seafood market located in the Riviera Maya and Cancun tourist areas to obtain added value and a price premium for their sustainably harvested lobster. They seek support for formulating a marketing plan to address these opportunities (Jain & Garderet 2011). A working capital loan to finance this integration is fundamental, particularly to withstand the 2 to 3 months credit expected by tourism-industry based clients, and to provide the opportunity to build up an inventory, in advance of the closed fishing season (see Figure 1-10/Figure 8-1). Loan funding with reasonably low interests rates ranging from 6 to 13% annual tariffs are required to provide the working capital for fishing operations and to purchase products from fishers associated with cooperatives. This would result in immediate payment of fished lobsters, whilst also providing trade credit to the tourism industry. In addition, the funds could be used to build a lobster inventory in advance of the closed fishing season, ensuring sufficient inventory for when prices are typically higher (Ley-Cooper 2009, Ley-Cooper 2010).



Figure 8-1: From: Ley-Cooper, 2014, RAZONATURA A.C. Summit TNC project. Shows the revolving capital fund initiative led by Integradora de Pescadores de Quintana Roo in collaboration with RAZONATURA, with additional funding from the Nature Conservancy and the Summit Foundation. It shows the ecolabelling scheme of lobster traceability from the BC and SK Biosphere Reserves, associated with a financial strategy for Working Capital.

Developing a traceability scheme related to ecolabels throughout the commercial chain, coupled with a sales strategy that is both more efficient and more directly linked to final consumers, would allow fishers to obtain higher prices for their lobster products, which are currently capitalized by middlemen who do not discern their origin or sustainability as a reason for added value (See Figure 8-1). This could be achieved relatively easily by individually labelling lobsters and solving the technical and administrative issues associated with temporary storage of live lobsters previously mentioned. Accumulating inventory or stock for selling at higher prices during the closed season would provide fishers with an opportunity to negotiate sale prices and to hold back inventory during those periods when there is excess supply on the market (Thomson & Caputi 2005, Penn et al. 2015). Similarly, final consumers can benefit from this arrangement, as they can help to pre-establish prices, payment terms and conditions, while receiving high quality, sustainable local products with a

branding strategy that helps their own corporate image as representing ecologically and socially sound businesses (Roheim 2008, Ley-Cooper 2010, Jain & Garderet 2011).

In 2010 the cost/benefit analysis of selling live lobsters against lobster tails in BC was predicted and was based on sale prices, income and expected volume of production applying the coffee model provided by Conservation International agency through the Wh-Leep Verde Ventures program in collaboration with RAZONATURA (Ley-Cooper 2009, Jain & Garderet 2011). It was possible to construct a similar model based on fishery and commercial data, and a yearly cash flow projection, incorporating monthly and total annual income and expenditure into the associated costs for transport and outsourcing storage for live or frozen whole lobster, tagged with an eco-label. In this projection, ecolabelling profitability and its payment capacity would be bound to a repayment scheme on the loan. This considered imposing an interest rate of 10% on the project's capital outflow over a period of 36 months, depending on the monthly income and profits generated annually as a result of the eco-labelling scheme.

The Chakay and MSC initiatives have been directly linked to the enterprise IPQRoo ("the client" in MSC's terms) which is still at a relatively immature stage of development. While considerable investment has been made in developing branding for a sustainable product, it is yet unclear whether or not the market will support this enterprise in the light of other commercial issues. In particular, there is a probability that current middleman in the chain of custody will intentionally repel this initiative to maintain their power for driving down cooperative prices. This represents a significant risk which will have to be planned for, however, cooperatives commercializing directly with the final consumer have already experienced a 30% increase with regard to dock prices, as shown by trial sales (Figure 8-1). It would thus probably be beneficial to increase the working capital fund initiative.

8.4 Socio-economics linked to sustainability through traceability and identity of origin.

Besides achieving sustainability for the *P. argus* population and its environment (MRAG-Americas 2013), the Chakay and MSC ecolabelling initiatives may offer an opportunity for fishing communities dependent on this resource to ensure their social and economic sustainability (Erol et al. 2009, Liu 2010). This is possible if ecolabels somehow incorporate fair-trade objectives into their principles and criteria, while leveraging market forces to attain tangible economic benefits for the fishing cooperatives (Liu 2010, Agnew et al. 2013, Ward & Phillips 2013).

Creating a direct commercial link between the fishers and the final consumers by tracing each lobster from the boat to the plate (hence applying “traceability”) is a key factor in this process (Figure 8-1). Commercial traceability provides a guarantee to the final consumer that lobsters are being fished sustainably from the SK or BC biosphere reserves, certifying that any added value goes back to its origin, as individual lobsters should be labelled (tagged) by the cooperative and fishers who originally caught them. A good example of a communication campaign of this nature is: www.thisfish.info, which allows access to detailed information for each individually tagged lobster (i.e. date, fisherman and place where it was caught), through a simple code associated to each label/tag.

When labelling and tracing sustainable lobsters as “Chakay”, the identity of origin (provenance) is reinforced by the registered slogan: “*Lobsters from the BC and SK Biosphere Reserves*”. In this way, ecolabelling practices can benefit each fisherman who engages in the sustainability scheme within SK and BC. The identity of origin is therefore a commercial and legal tool (IMPI 2009) that can directly generate economic benefits through recognition of sustainable practices. These mechanisms may also help regulate and control landing numbers as well as inventory by excluding illegal catch, thus deriving in general improvements in fishery management practices (Ley-Cooper 2010, Ward & Phillips 2010). Added value can be attained by promoting sustainable lobsters which are exclusive to the BC and SK Biosphere Reserves (IMPI 2009), in a way similar to that applied to products like the world famous drink Tequila (which owes its name to the small town in the state of Jalisco Mexico where it is produced from the agave plant species (*Agave tequiliana* Weber)). .

There are some banking restrictions related to the investment of working capital in fishing cooperatives (see Figure 8-1); as most cooperatives fail to meet the criteria required by banks for lending credit funds of this nature. Fisheries are considered by Mexican banks as a high risk investment from a business perspective, mainly due to uncertainties concerning yearly production volumes, potential income, and price fluctuations which are highly dependent on the US dollar. Without a significant upfront investment for working capital, business related to ecolabelling in Mexico will not be feasible.. However, the sustainability principles standing behind these initiatives, and the potential investment return on fishers’ welfare, and consequently ecologic and environmental gains seem to make these efforts worthwhile (Jain & Garderet 2011).

As well as helping overcome the historical debt barrier, the working capital financial arrangement combined with the Chakay/MSC ecolabelling schemes have produced other benefits for local cooperatives. By pursuing a business type loan rather than receiving government subsidies and grants to support this endeavour, fishers have been pushed to develop new business capabilities and skills thus an excellent opportunity has emerged to link sustainable fishing practices to self-sustained economic viability for local cooperatives. IPQRoo is a structured enterprise that is a hybrid between business and a non-profit organization, the support it has received has shortened the supply chain, and has capitalized the value of sustainable fishing practices by up to 30% more than regular dock based sales (Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper 2010, Jain & Garderet 2011).

The Chakay/MSC experience is likely to be replicable in other MPA's throughout the MBRS region. Although for this to occur, the need for enforcement of fishing regulations in these areas must be recognized, as the fishing communities in SK and BC have a historically established and strong commitment to the management of these Biosphere Reserves dating to an era that precedes them being declared MPA's. This recognition of community enforcement of regulations represents the key to the success of this venture (Sosa-Cordero et al. 2008, Ley-Cooper 2009, Ley-Cooper 2010, Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011, Gardner et al. 2013). If these initiatives want to prosper in the near future, any added value associated with the ecolabelled lobsters should result in a tangible economic percentage gain in price, which in turn should not remain in the hands of IPQRoo or cooperative administrators, but actually filter down to the individual fishers who show themselves willing to engage in sustainable schemes.

8.5 Economic and social stewardship for achieving sustainability in the SK and BC fisheries.

Sustainability principles and standards may be discrete or unknown to certain people, somewhat exclusive, or even biased and subjectively applied, depending on the controlling agency, organization or individual that establishes the criteria for "sustainability". In Mexico this means there is no general agreement on how sustainability is perceived, defined, or what is its exact meaning in the context of fisheries (Pérez-Ramírez et al. 2012b, Pérez-Ramírez et al. 2015). These and other issues regarding eco-labelling standards for sustainability have been well detailed and discussed in the book by (Ward & Phillips 2010), and recently

resumed in (Phillips 2013), confirming that MSC has been recognized as one of world's leading initiatives for creating, publishing and constantly updating its criteria for evaluation and standards for sustainability (Marine Stewardship Council 2010)..

The implementation of independent management programs and a permanent lobster monitoring plan in BC and SK, should be framed within the Yucatan Regional Management Plan for *P. argus* lobster (Ríos-Lara et al. 2012), and directly linked to the principles established in the sustainable eco-labelling initiatives at Chakay and MSC (see section 10). Fishing cooperatives and other stakeholders including NGO's, academia and government agencies associated with these fisheries need to collaborate in these programs that may conform or reinforce steering committees (Fletcher 2005, Ríos-Lara et al. 2012, Bellchambers et al. 2014, Velez 2014). This collaboration should then lead to initiatives being implemented for sustainable harvesting, and fair trade business practices (Liu 2010), (Donohue et al. 2010)..

Management and monitoring programs that adhere to a structured, design focussed on long term implementation, , are likely to provide the knowledge necessary for producing sustainable harvest control rules (HCR's) while simultaneously designing alternative bio-economic management opportunities for fishing communities (Morgan et al. 2009, Penn et al. 2015). Developing sustainable management schemes that propose alternative approaches for harvesting should imply direct economic benefits for the fishing communities, as it is estimated that over 300 families would be directly benefitted by these in both SK and BC reserves (Ley-Cooper 2009). Wise investment for these ecolabelling initiatives as an approach for conserving *P. argus* populations may provide examples for creating sustainable fishing models, that could be reproduced in other MPA's in the MBRS which are facing similar issues (Seijo 2007).

The first years implementing the Chakay's/MSC eco-labelling initiatives have provided information, data, management tools and consequently better knowledge of the long-term needs for improving sustainability of the spiny lobster fisheries in SK and BC, all of which can be applied throughout the MBRS region (Ley-Cooper 2010, Pérez-Ramírez et al. 2012b, Ley-Cooper et al. 2013, Bellchambers et al. 2014, Ley-Cooper et al. 2014). These eco-labelling initiatives have helped reveal potential livelihood benefits derived from reaching the objectives stated in the ecolabelling initiatives (IMPI 2009, Ley-Cooper 2009, Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper 2010, Marine Stewardship Council 2010, Ward & Phillips 2010), and it is now clearer how scientific knowledge may guide

management strategies, can propose changes in effort and fishing gear, and may help direct policies that will more likely engage stakeholders if added value is guaranteed. Bearing in mind the example given previously, that there was a 33% gain in price and triplication in landing volumes in BC, just from catching and selling lobsters alive instead of only tails (Ley-Cooper 2009), it has been demonstrated that tangible economic benefits in the SK and BC cooperatives are linked to successful conservation initiatives related to ecolabelling.

In a developing country like Mexico where a high percentage of the artisanal fishers are small scale and live in relatively poor conditions (Pérez-Ramírez et al. 2012b), the SK and BC MPA's experience has shown that, compliance with sustainable principles is greater if socio-economic benefits reach the lowest levels of the commercial chain (Ley-Cooper 2010). By incorporating the fair trade labelling principles (Liu 2010), into a broader and more holistic socioeconomic approach for ecolabelling, added value will be appreciated by fishers associated with cooperatives (Ley-Cooper & Quintanar-Guadarrama 2010, Ward & Phillips 2013), in the form of increased income.

The success of initiatives such as the ecolabelling programs and the implementation of no take zones (NTZ) in the SK and BC MPA's, is related to workshops explaining the potential values of conservation, where productive relationships between local fishers, government and Mexican NGOs (Pérez-Ramírez et al. 2012b, Velez 2014) are established. For example those fishers who participated in the selection of NTZ in SK and BC, strongly appreciated the opportunity to contribute to the process in the workshops , rather than having NTZ imposed by a top-down process; it thus appears that ownership and engagement during the decision making process are likely to improve compliance (Velez 2014).

Uncertainties regarding the MPA's role in general, and their long-term ecological value, already exist amongst fishers, and the complexity of understanding the real value of any conservation initiative, whether it is called NTZ, MSC or Chakay is often expressed. Given the fact that the SK and BC are ecological systems that harbour only portions of the *P. argus* meta-population, how specific management measures may affect lobster fisheries stock status and local population dynamics (see section 9.1) is also uncertain for most stakeholders. This suggests that future collaborative processes, focused on creating management measures for these fisheries, require a stronger grounding in ecological assessment and a more deliberate integration of ecological and social criteria in the process (Bellchambers et al. 2014, Origlio et al. 2014, Velez 2014).

The Chakay and MSC ecolabels in BC and SK are increasingly being recognized as exemplary models for adding value to management schemes and social arrangements that guarantee sustainable use of collective biological resources and ecosystems (Agnew et al. 2006, Ley-Cooper 2009, Ward & Phillips 2010, Jain & Garderet 2011). Overfishing for lobsters in similar ecosystems throughout the MBRs (FAO 2011, Ward & Phillips 2013), is an issue that could readily be helped with replication of initiatives such as these ecolabelling schemes (Ley-Cooper & Quintanar-Guadarrama 2010, Cambridge et al. 2011.). The introduction of casitas and campo ownership arrangements which are designed to provide individual economic returns from well-managed, communally owned biological resources would thus be particularly advantageous (Sosa-Cordero et al. 2008, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013). Ecolabels of this nature could provide the tools for refining management, scientific assessment, evaluation for stock improvement and addressing the reduction of environmental impacts throughout the MBRS (Caddy & Seijo 2005, Agnew et al. 2013, Bellchambers et al. 2014).

Lobster fisheries in SK and BC are vulnerable to economic undercurrent dynamics occurring in Mexico and the rest of the world, as revealed when the demand shrunk during the 2009-10 season due to the drop in the stock market, followed by the recession (Ley-Cooper 2009, Bernard 2010, Ley-Cooper 2010). The reduced tourist influx and local lobster consumption was also affected by the H1N1 swine-flu crisis, and the credit crunch deprived both small processors and fisher cooperatives from saving revenue for working capital, as a result of the cut back in sales. In the chain of custody, financially strong middlemen with working capital took advantage of this general crisis by widening the gap between fishers and final retailers, as they decreased the buying price to fishers by up to 40%, whilst restaurant sales either maintained or increased prices (Ley-Cooper 2010). If suggestions to implement ecolabelling schemes as coherent management strategies are not followed through (see section 9.3.) (MRAG-Americas 2013), and no harvest control rules are put in place (see section and 9.3.3.1.2), the future risk from similar economic scenarios which destabilize the Mexican economy, could result in an undesirable increase in fishing effort.

Mexican *P. argus* fisheries still have several issues that they must target in terms of management, regulation, and compliance for the benefit of the species (Caddy & Seijo 2005), in the context of the historical cooperative structures which have enabled good management practices being maintained and valued (Seijo 2007, Sosa-Cordero et al. 2008, Origlio et al. 2014). As the market forces have conditioned and pushed prices down, many fishers working

outside the SK and BC protected areas have been forced to bypass their administrative structures, and are willing to sell their fished lobster illegally, leaving authorities with little possibility of tracing the products' origin or assessing catches, thus favouring black market processors and fish brokers. Illegal fish- market booms of this nature promote a strong competition in price, and may result in an increase in fishing effort and a lack of compliance with legislation throughout the coastal area. Ecolabelling schemes and effective tracing of lobster from the boat to the plate are the means to combat this situation (Figure 8-1).

Low income families of artisanal fishers who work in BC and SK are beginning to appreciate the economic benefits derived from adding value to lobster fished in a sustainable manner so they have adopted ongoing suggestions for changes in technology and fishing practices (Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011). Applying the Chakay rules of use (IMPI 2009), carrying out scientific formal risk assessments on a yearly basis (Fletcher 2005, Bellchambers et al. 2014), and following the suggestions derived from MSC formal evaluations (MRAG-Americas 2013); may result in more effective management strategies with appropriate harvest control rules (see sections 9.3.3), thus optimizing exploitation of these fisheries. Furthermore, the use of bio-economic criteria to maximize benefits and balance fishing effort with yield (Puga et al. 2005, Ley-Cooper & Chávez 2009, Morgan et al. 2009, Gardner et al. 2013), would contribute to the long term sustainability of these fisheries.

9 Chapter 9 GENERAL DISCUSSION

The lobster *P. argus* fisheries in the SK and BC Biosphere Reserves in southern Mexico are the main cultural and economic activity that sustains the livelihoods of over 300 families within these Biosphere Reserves. *P. argus* is the most fished and highly-valued single species in both areas (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014) (Velez 2014). In this study, sustainability aspects were assessed and analysed using a wide range of techniques including traditional fishery science, mark and recapture methods, population genetics and stock assessment modelling procedures. New knowledge was gained as results included evaluations of the current status of these fisheries, which led to the discussion regarding the biology of lobsters, population dynamics and management arrangements used in the existing Chakay and MSC ecolabelling schemes.

The structure of this chapter follows an order within which the specific aims and objectives of the thesis are addressed and touched upon at least once by addressing the following concepts: a) stock status of the fisheries; b) environmental aspects; c) management and social issues; d) management suggestions for the future, and ends with a proposal for future research. Therefore the outline followed is not the conventional structure and it is similar to that which the MSC uses for evaluating fisheries sustainability status for the purpose of convenience, practicality, and direct applicability for stakeholders involved in these fisheries (Marine Stewardship Council 2010, MRAG-Americas 2013, Bellchambers et al. 2014). As has been detailed in (Chapters 1,4, 5, 6, and 7) Ley-Cooper et al. (2013,2014), biological aspects of this species were examined by means of fishery science techniques which formed the basis for developing and applying stock assessment modelling procedures and methodologies for estimating population parameters such as fishing mortality, exploitation trends and relative distribution of these lobster populations. Results obtained from field work and experiments constitute the core criteria for evaluating sustainability of the BC and SK fisheries against existing standards (Marine Stewardship Council 2010), and are used to discuss potential for an improvement in current and future fishery and management practices.

Conservation initiatives, as well as changes in management and fishery practices have been applied during the time frame of the current research. These are further discussed here in the light of published information. Changes in the fisheries include the elimination of the gaff/hook with the introduction of a snare loop as a new technique to capture live lobster in

BC, and the implementation of casitas in the area (reviewed in Chapter 4). Economic and social stewardship in these fisheries is revised and compared on a world scale to other MSC certified lobster fisheries (Bellchambers et al. 2014). The genetic analysis of the local lobster populations in BC and SK (Truelove et al. 2014, Truelove et al. 2015) and the Mesoamerican Reef Region (Truelove 2014) is also discussed within the framework of this thesis. Socio-economic aspects of the fishers and the current status of the existing ecolabelling initiatives a) *the Chakay collective brand* (Ley-Cooper & Quintanar-Guadarrama 2010) and b) the *MSC certification* (MRAG-Americas 2013) were investigated and evaluated, including an analysis of how stakeholders and markets interact in relation to these schemes.

9.1 Evaluating the SK and BC fisheries sustainability

The SK and BC fisheries have already been declared “sustainable” after being evaluated by a third party audit against MSC standards, principles and criteria, and have achieved the required aggregating scoring values above 80 points (Marine Stewardship Council 2010, MRAG-Americas 2012). Through open consultation amongst stakeholders and experts, as well as a public scrutiny, the evaluation assessed the status of the stocks (P1), the environmental impact of the fisheries (P2), and effective management (P3) in 2012 and 2013 (MRAG-Americas 2013). For this reason, the inclusion of these concepts becomes obvious when assessing sustainability aspects of the SK and BC fisheries.

The credibility, values and attributes of the different principles and criteria used for assessing sustainability of a fishery are highly dependent on the level of complexity behind the science and evaluation methods, and the level of detail by which each element is judged (Cruz 2002, Pauly et al. 2002a, Ley-Cooper 2010, Marine Stewardship Council 2010, de Lestang et al. 2012, Bellchambers et al. 2014). Whether or not these elements included in the assessment encompass social, economic, ecological, environmental, or management factors, the credibility of these factors also partially depends on how they are framed and integrated into the assessment documents used by the authors/auditors who are responsible for describing and interpreting them.. The level to which a fishery evaluation scores against distinct standards and principles for sustainability, will be less dependent on the authors/auditors interpretation, if the criteria are highly standardized, supervised or peer reviewed during assessment processes.

9.1.1 Social and bio-economic standards for achieving sustainability

Assessment of cooperatives has evidenced that the SK and BC fisheries cannot be evaluated as a single unit from an economic and financial perspective (section 8.4), as each cooperative has its own administration, accountability scheme, financial benefits and limitations. Furthermore, the majority lack comprehensive economic and social studies to enable assessments of this nature. Socioeconomic principles and criteria have not yet been developed or used as reference guidelines for third party evaluations in these fisheries. The task of defining the *P. argus* fisheries in BC and SK as “sustainable” from a multidisciplinary socioeconomic perspective has been insufficient and has lacked the availability of necessary data (Ley-Cooper & Chávez 2009). Consequently there is still a need to produce further guidelines and reference points that could be used for on-going performance evaluations (Roheim 2008).

Achieving sustainability in the lobster fishing industry in developing economies like Mexico is highly dependent on socioeconomic factors which extend beyond local fishing operations (Ley-Cooper 2010), as is the case with other fisheries around the world (Cinner et al. 2009, Erol et al. 2009). Seasonal increase in fishing effort (Ley-Cooper et al. 2014) can be caused by lobster recruitment to the fisheries and their movement patterns as well as environmental factors such as cold fronts (“Nortes”) (see Chapters 6 and 7) (García et al. 1991, Drinkwater et al. 2006). Increase in fishing effort may also be influenced by anthropological factors and fisher’s behaviour (Defeo & Castilla 2005, Puga et al. 2013), when responding to the costs and prices of fishing transactions (Seijo & Caddy 2000, Ley-Cooper & Chávez 2009, Jain & Garderet 2011). The latter highly depend on the seasonality of tourist influx, and the ongoing fluctuation of local currency against the US dollar. In order to safeguard fishery management against potential surges in fishing effort leading to rises and overexploitation, socioeconomic elements should address and include independent evaluations for each of the six participating cooperatives in SK and BC. Bio-economic assessments including cost/benefit analysis require updated and detailed data which is more comprehensive than that, which was generated for running the FIMSO model for BC (Ley-Cooper & Chávez 2009). Regardless of the accuracy of previous assessments carried out and precision of the economic data input, it is reasonable to suggest that if socio-economic criteria were to be used for evaluating long term sustainability of these fisheries, two or three out of six fishing cooperatives operating in both MPA’s would not meet all requirements.

Two of the six cooperatives operating in BC and SK have been historically entangled in a permanent debt cycle with banks and industrial intermediaries, their yearly income barely balances out with expenses and investments made throughout the fishing season. This has left these cooperatives without utilities and savings to invest in operations for the following season and has obliged them to maintain a financial debt with the intermediaries who are willing to pay upfront for unfished lobster (Ley-Cooper 2009, Jain & Garderet 2011). The standard Mexican banks, charging yearly interest rates of up to 12%, require existing material assurance of their lending capital (buildings, boats, vehicles, etc.) in order to invest in fisheries, and are unwilling to take investment risks on unfished product/lobster. Therefore banks do not provide working capital directly to fishing cooperatives, thus favouring the intermediaries. The long term unsustainability of these financial arrangements for fisheries has been made obvious, since relying on upfront loans implies very high interest rates and results in limited added value for fished lobster.

Establishing and implementing internal financial and administration control systems, and creating the second tier enterprise called Integradora de Pescadores de Quintana Roo, have aided financial independence in some of the cooperatives by achieving a higher- price negotiation power and reducing cumulative debts and costs (Ley-Cooper 2009, Ley-Cooper 2010, Jain & Garderet 2011). These practices and control systems have given a certain level of financial stability to these cooperatives which should be extended to others because they offer an approach which safeguards the fisheries against increasing effort (Cinner et al. 2009). Otherwise, the eminent risk is that higher exploitation rates will occur in order to pay high interest loans in response to unstable underlying market forces (Roheim 2008, Lomax 2009). In this scenario, lobster stock sustainability may become a secondary priority. thus it is imperative to carrying out socio-economic monitoring assessments, and to establish a series of guidelines to manage these fisheries, taking a bio-economic approach to maximize economic benefits (Gardner et al. 2013), while guaranteeing future stock and economic financial sustainability (Puga et al. 2005, Thomson & Caputi 2005, Ley-Cooper & Chávez 2009) within these MPA's.

9.1.2 Stock environmental and management sustainability standards

The MSC ecolabelling program is currently and increasingly one of the most renowned certifying initiatives (MSC 2014) which has set a reference standard for evaluating sustainability of exploited fisheries (Ward & Phillips 2010). Although the program does not include extensive social or economic considerations, it is well structured around the idea that

certified fish come from “*a well-managed and sustainable source*” on the basis of the three main principles: (P1) *Principle 1 Sustainable fish stocks*; (P2) *Principle 2 Minimising environmental impact*; (P3) *Principle 3 Effective management*. The performance of the SK and BC *P. argus* fishery in relation to MSC Principles was evaluated as being sustainable after achieving a PASS with P1=81.8, P2=87.0 and P3=82.1 points awarded once the full assessment was completed. This qualification was published in 2012 (MRAG-Americas 2012). Some knowledge and management gaps have been identified in the certifying process, requiring attention from all interested stakeholders, or those in any way involved in management, research, or industry. A series of conditions have been established in order to maintain the MSC certification in these fisheries, and a working program to address relevant issues has been drawn up, which is to be evaluated on yearly basis by a third party surveillance visit (MRAG-Americas 2013).

The outreach capacity and full applicability of the MSC standards in developing countries is questionable as many fisheries are normally data deficient (Pérez-Ramírez et al. 2012b), and have a limited budget for comprehensive assessments. The criteria, scientific tools and data produced for evaluating sustainability of the BC and SK lobster fisheries is also limited by the scope and time frame available to complete assessments. However, a conclusion based on the results of the research for this thesis is that it is valid and sound practice to refer to the MSC standards as a framework to discuss the sustainability of lobster fisheries in BC and SK southern Mexico, (MRAG-Americas 2012, Agnew et al. 2013, MRAG-Americas 2013, SCS 2013).

9.2 Defining the biological management unit in the SK and BC MPA’s; an assessment of connectivity levels from a genetic perspective.

There are uncertainties regarding the definition of the biological/management units for the SK and BC lobster stocks (see section 1.6.2), as well as in the processes that drive local populations and/or fishery recruitment. The deficiencies in the international scale of management can greatly complicate matters, if most larval recruitment depends on other areas, outside of these MPA’s (MRAG-Americas 2012). There is limited data to evaluate the levels of larval self-recruitment, and local stocks are likely to be associated with a regional population extending south to Honduras /Nicaragua, influenced by the northbound ocean currents prevailing in the Yucatán (Briones-Fourzán et al. 2008, Muhling et al. 2013, Truelove et al. 2014). This unsolved issue has led to the application of the SICA (Scale, Intensity and Consequence Analysis) procedure for stock status (P1) (Marine Stewardship

Council 2010, MRAG-Americas 2012) (MRAG-Americas 2013). No contradicting theory to the SICA procedure has yet been posed, although new light has been shed on it by using microsatellite genetic analysis for understanding connectivity between the populations at a regional level in the MBRS (section 1.5.1) (Truelove et al. 2014) and at a local level between the BC and SK areas (section 1.5.2)(Truelove 2014, Truelove et al. 2015). This genetic analysis and connectivity are discussed in the following paragraphs to address the issue of the “biological management unit”.

9.2.1 Regional connectivity

Oceanographic studies and biophysical modelling techniques for simulating larvae transport have proposed that the SK and BC vicinity is probably highly dependent on larval recruitment from distant source populations delivered via transport on the northbound flow of the Caribbean and Yucatan current (Briones-Fourzán et al. 2008, Butler et al. 2011, Muhling et al. 2013). As discussed in section 1.3.1 and 1.5 and detailed in Truelove (2014), population genetics results showed increased “immigration” levels to local populations in the northern MBRS, which suggested that spatial patterns of genetic differentiation in these *P. argus* populations could be driven by long-distance dispersal. Biophysical modelling (Butler et al. 2011) (see Figure 1-11), has also suggested that *P. argus* populations, particularly near the Sapodilla Cays MPA’s (see Figure 1-12) may be more dependent on self-recruitment from locally derived stocks, than areas further north such as SK and BC.

The SK population appeared to vary from the general trend as it was more differentiated from all other MPA’s, in terms of positive spatial autocorrelation and genetic variance, and it presented, along with populations from other MPA’s, the spatial principle component eigenvalue with the greatest amount of global structure, (Caye Caulker, Hol Chan, and Alacranes Reef) (Truelove et al. 2014). As suggested by (Muhling et al. 2013), a combination of spatially and temporally targeted spawning effort and larval behaviours may promote some degree of larval retention, so the results observed in SK could also be a consequence of a distinct larval retention pattern occurring as a result of local oceanographic processes. However this result must be judged with relative caution as the sample size, time frame and lobster size classes evaluated were all limiting factors in this study, and unique individuals (outliers) may have significantly influenced the statistical results.

Sample size and time frame to compare a) genotypes of lobster post-larvae that recruited to a specific MPA with b) genotypes of adults residing within the MPA, also

represented a limiting factor in the population genetics regional study (section 1.5) (Truelove et al. 2014). However, it is probable that the rare individuals found in SK and Alacranes Reef were unrelated to all the other individuals, as they derived from larvae recruited as “migrants”(Truelove et al. 2014), and originated from other “source populations” that were not sampled, such as Cuba. This is plausible, if we consider the vicinity of Cuba to SK and Alacranes, as well as evidence from the oceanographic studies carried out by (Muhling et al. 2013), which showed that the westward trajectory of the Caribbean Current impinged upon the Yucatan Peninsula at a latitude of approximately 18°N, east of Banco Chinchorro, before flowing northward along the coast, and passing through the Yucatan Channel into the Gulf of Mexico.

The hypothesis that self-recruitment may provide MPA’s with locally derived rare alleles is unlikely, but it is an alternative explanation for the spatial patterns of genetic differentiation that were observed as part of the sibling analysis (Truelove et al. 2014). Whilst results provided evidence of immigration and increased proportions of siblings within MPA’s, there was not sufficient data to conclude which one of these factors was the most important for driving the spatial patterns of genetic differentiation that were observed (see section 1.5, (Truelove et al. 2014)). Resolving this uncertainty will require incorporating genomic techniques and conducting temporal comparisons of larval and adult spiny lobster genotypes throughout the given MPA’s. Future research should thus monitor a wide range of size structures including adult, juvenile and larval samples, over a longer time period, to evaluate recruitment variability and seasonality changes. The results from these investigations would provide indications concerning population differentiation which is relevant to management at a regional level.

It is inferred that the SK and BC *P. argus* populations are components of a larger meta-population with high levels of genetic exchange and should therefore ideally be managed as a larger scale unit at a regional level. The high level of genetic connectivity identified among MPA’s provides additional evidence of interdependence for recruitment of *P. argus* in the MBRS (Figure 1-12), so management should stress the importance of international cooperation in Central America stretching beyond the BC and SK boundaries (Tewfik et al. 1998, Truelove 2014); Furthermore management planning for the MBRS should probably include in La Moskitia and Bocas del Toro in Panama, as well as Cuba.

9.2.2 Chaotic genetic patchiness and connectivity between SK and BC

In the studies by Truelove et al. (2014), Truelove et al. (2015) the sampling design to evaluate local population genetics and connectivity between SK and BC admittedly has certain limitations (reviewed in section Population genetics in Sian Ka'an and Banco Chinchorro 1.5.2) since: a) BC and SK are two sites which are geographically neighbouring each other by less than 200 km (see Figure 1-2); and b) the study had a relative small sample size ($n=140$), which impedes a thorough analysis of the biological context. It is therefore not surprising that results from this analysis found no evidence of differences in population structure between the BC and SK *P. argus* samples ($P = 0.139$) (Truelove et al. 2015).

Paradoxically the SK population did show a genetic differentiated structure when compared against other MPA's in the MBRS (including of BC) within the regional context (section 1.5.1), (Truelove 2014). This implies that additional evidence is needed to better understand the levels of connectivity between these SK and BC MPA's. Results could potentially change the perception of how the biological/management units are conceived in SK and BC, and therefore affect the framework criteria used for defining these units as "independent" in the context of population evaluations and assessments for MSC (MRAG-Americas 2013). The regional findings by Truelove et al. (2014) encouraged further processing of the SK and BC lobster samples at a local scale, by using different statistical methods and population genetic techniques (BIC and DAPC). The approach was to group the same lobsters samples into separate cohorts/size classes (Figure 1-13 and Figure 1-14) (Truelove et al. 2015).

Irrespective of the results presented at the local level of analysis (see section 1.5.2) (Truelove 2014, Truelove et al. 2015), it is unlikely that the BC and SK sites should harbour genetically differentiated population(s) within the *P. argus* species, as its life cycle entails a long larval period which promotes long range distributions (Briones-Fourzán et al. 2008, Butler et al. 2011, Naro-Maciel et al. 2011, Truelove et al. 2014); unless the SK and BC sites reveal a pattern of chaotic genetic patchiness (Kennington et al. 2013). Genetic patchiness suggests that populations found a few kilometres apart can be as genetically different as populations separated by distances of hundreds of kilometres, or simply temporarily unstable, since differences between local populations emerge and disappear across generations (Larson & Julian 1999). Since different processes can cause temporal variation in the recruits, including natural selection or changes in the source population, (Larson & Julian 1999,

Kennington et al. 2013), a case of genetic patchiness is a potential explanation for the patterns observed in the analysis for BC and SK (section 1.5.2).

Regional results reviewed in section 1.5.1 (Truelove et al. 2014) and previously discussed in section 9.2.1 and 9.2.2, indicated a certain level of differentiation in population structure with the positive spatial autocorrelation and the genetic variance observed among SK's lobster population with regard to other MPA's, including BC (see Figure 1-13 and Figure 1-14)(Truelove et al. 2014). This differentiation provides evidence for the possibility of genetic patchiness occurring among *P. argus* populations within these two areas (see Figure 1-10 and Figure 1-14. (Truelove 2014)), based on the assumption that the process could be driven by oceanographic factors where distinct ecologic or oceanographic dynamics can affect larval recruitment patterns (Muhling et al. 2013) influenced by distance and bathymetric physical barriers such as the 1000m deep channel that separates these two MPA's (Jordán & Martín 1987, Contreras-Silva et al. 2012). However, this hypothesis cannot be confirmed as there is no evidence of differences in population structure between the BC and SK *P. argus* samples, when these are independently assessed (Truelove et al. 2015).

On the other hand, the differentiation among size classes in both SK and BC (Figure 1-13) (Truelove et al. 2015) favours the idea of connectivity between both SK and BC MPA's, because genetic patchiness is also possible as a result of temporarily unstable differences between local populations, which emerge and disappear across generations as a result of temporal variation in the recruits (Larson & Julian 1999). If so, the differences observed between generations/size classes may occur as a response to larval settlement pulses, settling simultaneously into both BC and SK sites (Briones-Fourzán et al. 2008), with changes in structure between generations, but originating from the same source populations found elsewhere in the Caribbean (Kennington et al. 2013) (Briones-Fourzán et al. 2008, Naro-Maciel et al. 2011). Regional findings (Truelove et al. 2014), suggest that *P. argus* populations may not be as genetically homogenous as mtDNA studies had previously concluded (Silberman et al. 1994 , Naro-Maciel, 2011 #256), so periodic pulses of larval recruitment settling simultaneously into both SK and BC from genetically distinct source populations is possible, considering that various processes can then cause temporal variation in the recruits following settlement, ranging from natural selection to changes in the source population (Kennington et al. 2013).

Chaotic genetic patchiness is most often observed among marine organisms with

planktonic larvae (Larson & Julian 1999, Kennington et al. 2013); and the fact that some lobster size classes are more noticeably uniform in terms of genetic cluster conformation than others (i.e. 90-100 mm) can be attributed to this effect. If we assume that larval recruitment pulses may be occurring at a similar rate and simultaneously in both the BC and SK (Briones-Fourzán et al. 2008, Muhling et al. 2013), and that these pulses are most likely to proceed from similar up-current sites found elsewhere south in the MBRS/Caribbean (Butler et al. 2011, Naro-Maciel et al. 2011), originating from the same source population(s), (Truelove et al. 2014), it may be that genetic patchiness results from natural selection after settlement, resulting either from temporal genetic variation in the larval pool, and/or combined with patchy settlement (Larson & Julian 1999, Kennington et al. 2013).

A clear example of how temporal variation of recruits can lead to genetic patchiness has been described for the western rock lobster (McWilliam & Phillips 1997) where allozyme variation was examined in monthly collections of puerulus of two sites nearly 350 km apart, (Johnson 1999). In this study there were no apparent allele frequency differences between sites in each monthly collection, but allele frequencies did change over time, so it was the combination of temporal variation in allele frequencies and contrasting patterns of recruitment that resulted in genetically different cohorts at the two sites. Considering the response to environmental and oceanographic changes in currents and temperatures (Briones-Fourzán et al. 2008, Butler et al. 2008, Muhling et al. 2013), the distance from SK to BC is short enough to assume that both lobster populations are subject to similar larval pulse settlement patterns, but that a combination of temporal variation in the allele frequencies and contrasting patterns of recruitment have resulted in genetically differentiated cohorts; in fact analogous in both BC and SK sites.

Results presented in section 1.5.2, indicate that distinct cohorts have been tailored within the same size class groups as an effect of the semi-arbitrary lengths that were established every 10 mm CL (Figure 1-14) (Truelove 2014, Truelove et al. 2015), otherwise recruitment pulse patterns would have had to vary according to similar time periods as those indicated by each size class. It is also likely that selection at one or two loci is driving the observed pattern, or that otherwise it results from a drift in a population with very small size (N_e). Results may also reflect a methodological issue caused by the difference in loci, with null alleles between clusters; thus future studies should include larger sample sizes, sample pueruli, monitor larval settlement, and be capable of identifying cohorts on a temporal basis, in order to arrive at more definitive conclusions.

Data from spiny lobster growth and size at maturity estimates suggest that different size classes of lobsters that were sampled from BC and SK were most likely recruited to these MPA's during different settlement periods, as temporal variation among the genotypes of new puerulus recruits may explain these results (section 1.5 (Selkoe et al. 2006,(Truelove 2014). Larval recruitment from distant *P. argus* source populations (Briones-Fourzán et al. 2008, Kough et al. 2013), and variation among the genotypes of individual *P. argus* lobsters and/or cohorts that recruit from these diverse sources, may explain the high levels of variation observed among the sizes classes. Irrespective of the causative factor, genetic connectivity at a local level between SK and BC, confirms the possibility of commonly shared genetic pool between sites (Truelove et al. 2014, Truelove et al. 2015), and has revealed the possibility that cohorts differentiate into genetic clusters, implying temporal variation among the genotypes of pueruli recruits (Selkoe et al. 2006, Larson, 1999, Kennington, 2013). This confirms that a regional approach to sustainable fisheries is the best guarantee of sustained recruitment by pueruli influx into these MPA's.

Natural selection may also be acting upon the new pueruli and juvenile recruits after they settle in nursery habitats in BC and SK (Larson & Julian 1999, Kennington et al. 2013), as *P. argus* is dependent on several different habitat types throughout its life history when conducting ontogenetic migrations from shallow hard-bottom nursery habitats to coral reefs (Butler et al. 2006,(Briones-Fourzán & Lozano-Álvarez 2013); where complex selective processes acting on new recruits, juveniles, or adults may also explain apparent variation in the adult population (Planes and Lenfant 2002(Truelove et al. 2015). Direct testing for genotypes of new larval recruits in BC and SK MPA's will be necessary in order to confirm the hypothesis that temporal variation among larval recruits is indeed responsible for the genetic differences observed among size classes, yet the analysis and discussion from Truelove et al. (2014, 2015) suggests that temporal variation in levels of genetic differentiation may positively contribute to the total genetic diversity of *P. argus* within Mexican marine reserves.

The fact that *P. argus* lobsters from SK were more differentiated from all other MPA's in terms of positive spatial autocorrelation and genetic variance (Figure 1-14a), leads us to assume that a certain level of self-recruitment may occur. However, if the results point to the belief that the "standing stocks" in SK and BC are completely dependent on recruitment from areas found elsewhere, the incentives for preserving the local breeding stock could be questioned by the local stakeholders, given that preserving egg bearing

females and large males does not necessarily guarantee local recruitment. To counteract this reasoning, it should be underlined that larvae exported from these two areas towards the north of the Caribbean, benefit other sites as far as the Gulf of Mexico and Florida (Ríos-Lara et al. 2007, Butler et al. 2011, Truelove 2014).

The BC and SK areas have been defined as “banks”, as lobster recruited to these areas do not substantially mix with other “banks”(MRAG-Americas 2012). However, the statement may be imprecise in the light of connectivity levels occurring between SK and BC and other MPA’s in the MBRS (See section 1.5.1 (Truelove et al. 2014)). The current application of the bank definition for BC and SK stands on the assumption that only the post-settlement benthic portion of the population/stock(s) should be evaluated for sustainability (see details in section 9.3.1.1.1), as larval sources are as yet uncertain (Naro-Maciel et al. 2011, Truelove et al. 2015).

As larvae are most likely sourced from populations found further south in the MBRS and Caribbean where breeding stocks are progressively being depleted by local fisheries (Ehrhardt & Fitchett 2010), a precautionary principle indicating the risk of a diminishing trend in larval/pueruli recruitment should be applied. Given uncertainty in terms of genetic intermixing concerning both larval recruitment levels and sources of origin for SK and BC areas, stock status should continue to be assessed and determined for the benthic juvenile and adult lobsters which have been recruited, whilst assuming an open population modelling framework. It is important to include and create a continuous monthly pueruli settlement index (Briones-Fourzán 1994, Briones-Fourzán et al. 2008) to monitor and address the potential risk of a reduced larval influx, which could affect both fisheries.

If the SK and BC share a common *P. argus* genetic pool and local spawning contributes to recruitment in other areas downstream as inferred by (Truelove et al. 2014, Truelove et al. 2015), management measures should guarantee that the proportional contribution of recruitment from those bank(s) to the shared meta-population is not impaired, as expressed in the MSC principles (MRAG-Americas 2012),(Marine Stewardship Council 2010). The absence of a mechanism to manage and maintain the entire meta-population at or above the Biological Maximum Sustainable Yield (Bmsy) suggests that managing the SK and BC MPA’s as independent “banks” is appropriate. Therefore local conservation projects such as the maximum size limit proposed for south SK (Sosa-Cordero 2014) and the casita initiative in BC previously detailed in Chapter 4, may benefit Meta-population of the species

by contributing to larval export from these areas, recruitment to others, and genetic diversity of *P. argus* in the MBRS and Caribbean region.

9.3 Sustainability performance indicators, status of the stock(s) (P1), environmental impact (P2), and effective management (P3) in Sian Ka'an and Banco Chinchorro

9.3.1 Status of the stock(s)

9.3.1.1.1 Boundaries and limits to the benthic, post-settlement “standing” populations

Uncertainty regarding the origin of local spiny lobster larval recruits (Briones-Fourzán et al. 2008, Butler et al. 2011, Naro-Maciel et al. 2011, Truelove et al. 2014); the intrinsic difficulty of defining the geographical boundaries which delimit the stock range (Acosta & Robertson 2003, Ley-Cooper 2006, Sosa-Cordero et al. 2008 (Acosta, 2003 #28, Bertelsen 2013); and knowledge gaps concerning the adult portion of the stock which annually moves and migrates to and from the deep unfished areas (>20 m) (Ley-Cooper et al. 2014); are all matters which concern the analysis of the local lobster population dynamics in BC and SK, and underline the need to agree on whether the stock of these areas should be treated as “single” or “shared” units for management.

The BC 1000 m deep and >30 km wide channel that separate the BC populations from the coast (Jordán & Martín 1987, Contreras-Silva et al. 2012), represents a natural barrier for the movement of benthic juvenile and adult lobsters (Ley-Cooper 2006). This barrier means that lobsters stay in BC once they have settled as pueruli and are recruited to the atoll as juveniles, given the limited movement capacity of the benthic juvenile and adult spiny lobsters beyond ≥ 200 m depths, which restricts intermixing within adjacent regions (Herrnkind 1980, Lyons et al. 1981, Lozano-Álvarez et al. 1993, Bertelsen 2013). As shown in chapters 0,6, and 7, a similar process occurs in SK, but to a lesser degree, because once lobsters have recruited to SK they are expected to remain within the boundaries of the MPA where they are heavily exploited, or else have minimal longshore exchange with lobsters to the north or south (Lozano-Álvarez et al. 1991b), as they have been reported to migrate mainly to and from the deep areas (>20m) or between both bays BA and BES (Lozano-Álvarez et al. 1993, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

High variability in recruitment levels and survival rates occur in multiple life stages of *P. argus* (Cruz et al. 2001, Ehrhardt & Fitchett 2010, Butler et al. 2011), and this complicates management when using reference indexes such as pueruli recruitment as occurs in other lobster species fisheries (i.e. *P. cygnus*) where this is possible (Gutierrez-Carbonell et al. 1992, Phillips et al. 2000, Briones-Fourzán et al. 2008, Donohue et al. 2010, Penn et al. 2015). As the level of pueruli recruitment is currently unquantified in BC, and highly variable in northern SK (Briones-Fourzán 1994, Briones-Fourzán et al. 2008) we must recognize that stock status can currently not include pueruli settlement indexes in the assessments, and are therefore constricted to being determined by the standing portion of the populations, consisting of the benthic post-settlement juveniles and adult lobsters (Briones-Fourzán & Lozano-Álvarez 2001b, Alvarez-Flores & Sosa-Cordero 2010). Thus I defined the local stock(s) as: all lobsters of measurable sizes, ranging from the benthic post algal juveniles to the large/reproductive adults, who are likely to be distributed in a wide diversity of habitats found within these MPA's throughout the span of their ontogenic life cycle (Briones-Fourzán & Lozano-Álvarez 2013, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014).

The assumption that SK populations are self-contained is likely, but partially challenged by evidence resulting from the tagging studies (Chapters 0 and 6), which also showed that a percentage of lobsters found in deep unfished areas (>20m) move into the shallow fished areas at an estimated rate of 15-20% per fishing season, indicating that recruitment into these fisheries from deep waters occurs, and that there is some level of unknown offshore adult connectivity between both bays of SK beyond the 20 m depth limit (Ley-Cooper et al. 2014).

In this study we also found that lobsters which had previously been tagged in Bahía de la Ascensión (BA) were recaptured further south in Bahía Del Espíritu Santo (BES). Some of these movements took up to two years, with lobsters covering a distance of about 43.5 km (Ley-Cooper, Ley-Cooper et al. 2013). The model described in Chapter 6, estimated that 80-85% of the total portion of lobsters found in the deep (>20 m) had escaped the fishery during the course of the study, by either temporarily remaining in the unfished area, by migrating elsewhere beyond the limits of these fisheries where tags were no longer recovered, or by dying from natural mortality (Bertelsen 2013, Ley-Cooper et al. 2014).

If lobsters previously tagged are recaptured outside of the limits of the SK Biosphere Reserve at a time after the conclusion of this study, there would be more evidence to favour

the extension of the limits of the reserve which currently mark the conceptual boundaries of the SK stock(s). Otherwise, the northern-BA (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 2008) and southern-BES bay's (Sosa-Cordero et al. 1999, Ley-Cooper et al. 2013), should continue to be assessed as independent units for estimating exploitation rates. A certain level of adult exchange between these bays occurs (Ley-Cooper et al. 2014) which should be further assessed and incorporated into future evaluations as well as modelling exercises for these SK fisheries.

9.3.1.1.2 Catch, effort, risk assessment and need for Harvest Control Rules

SK and BC have been awarded a pass score, when evaluating the (P1) stock status by MSC standards that refer to several criteria. Factors include, but are not limited to: a) relatively well-managed fisheries (Sosa-Cordero et al. 2008); b) they are considered small scale (Seijo 2007); c) have restricted access as MPA's (INE-SEMARNAP 2000, CONANP 2007); d) certain input control systems/effort limitations are in place (Gardner et al. 2013); e) fishery exploitation rates are high but limited to shallow depths (< 20 m), allowing only free diving (Ley-Cooper et al. 2013); f) the SK cooperatives use casitas considered as relatively low impact fishing gear (Briones-Fourzán & Lozano-Álvarez 2013); and g) the campo systems in place represent an exemplary case of territorial use rights (Sosa-Cordero et al. 2008, Conrad 2011, Gardner et al. 2013). These and other factors are further discussed in this sub-section.

As shown for south SK in chapters 5 and 6, and in Ley-Cooper et al. (2013), following a critical stage that occurred in the 1980's, (Lozano-Álvarez et al. 1991b, Ríos-Lara et al. 2012), exploitation rates in the SK and BC have continued at a relatively stable level up to now, and are presently fully fished with moderate to high levels of exploitation (Alvarez-Flores & Sosa-Cordero 2010, Ley-Cooper et al. 2013). However, given the lack of consistent robust information on stock status, the target stock status performance indicator (MSC P1), required the Risk-Based Framework (RBF) to score these fisheries (MRAG-Americas 2012). Up until the latest assessment carried out in 2013, these fisheries still met the MSC stock status requirements (MRAG-Americas 2013), when using the Productivity Susceptibility Analysis (PSA) (Marine Stewardship Council 2010), yet most recent studies agree that effort should not increase beyond current levels (Sosa-Cordero et al. 2008, Ley-Cooper & Chávez 2009, Ríos-Lara et al. 2012, Ley-Cooper et al. 2013).

Uncertainties regarding exploitation rates and stock status require further data gathering and updating of fishery based information, as well as independent surveys, along with new and more precise information on fishing effort and relative abundance indexes (Seijo & Caddy 2000, de Lestang et al. 2012). As well as anthropogenic impact, the effects of environmental variables on effort should be monitored more closely, (Puga et al. 2013), since changes in temperature, wind strength/direction, and influxes of rain water may produce variations in abundance, catchability and catch rates (García et al. 1991, Drinkwater et al. 2006). This has been discussed in detail in Chapter 7.

9.3.1.1.3 Limited entry:

A limited number of licences are awarded to fishers associated to one of the three cooperatives, boat permits are renewed annually and cooperatives must comply with current legislation (Ríos-Lara et al. 2012). Limited entry to fisheries as a stand-alone regulation may not necessarily guarantee restriction on effort, as participants may continue to compete for resources by improving other aspects involved in fishing effort, such as vessel capacity and thus overall catch potential (Ley-Cooper & Chávez 2009, Gardner et al. 2013).

To date, number of trips has been considered as the best indicator for measuring effort (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 1999, Sosa-Cordero 2003, Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), so regular monitoring of effort is needed by registering the number of trips, the number of fishers on board and time spent searching both at the surface and under water, as these factors are bound to change as a result of technological development and fishing gear diversification. Besides weather, changes in the ecosystem, and macroeconomic conditions, another factor that could determine catch levels on each trip is the number of temporary unregistered crew members known as “aspirantes”, effectively increasing effort per trip.

Another factor to consider is that more effort has been exerted on specific fishing locations as has been evidenced in certain Campos in BA-SK (Chapter 7). Increased effort is probably attributed to length of the trips to a given site, the number of fishers that access the site, and the use of technology like GPS which allows for higher efficiency in locating known refuge sites and casitas. The number of trips as a measure of effort should be closely monitored, if new gears like casitas are to be introduced in BC, as suggested in Chapter 4.

9.3.1.1.4 Territorial use rights:

Individual transferable grounds (ITG) grant right of access to particular fishing areas/territories (Gardner et al. 2013), as is the case of SK where fisheries have co-managed the resource with a history of sound decision making (López & Consejo 1986 , Lozano-Álvarez et al. 1989, Lozano-Álvarez et al. 1993, Sosa-Cordero et al. 1998). Lobsters that are fished with casitas occur in the exclusive access parcels/lots called Campos, owned by individuals or families and administered by the cooperative's council (see section 1.6.4.1.1) (Lozano-Álvarez et al. 1991b, Sosa-Cordero et al. 2008, Ley-Cooper et al. 2013). This property arrangement is unique, as it virtually divides the sea floor into a series of concession blocks allotting territorial ownership to individuals with the aim of improved resource management (Section 1.6.4.1.2) (Seijo & Fuentes 1989). Individual fishing property rights over the Campos promote a self-help approach to community development, and an institutional framework that assigns exclusive property rights to fishing cooperatives (Gardner et al. 2013). This property arrangement provides an exemplary model of territorial use rights (Briones-Fourzán & Lozano-Álvarez 2013), probably the best warranty for managing and guiding fisheries towards sustainability in the long run.

9.3.1.1.5 Illegal fishing:

Lobster fisheries harvesting effort exerted by the cooperatives in these MPA's is closely monitored, yet the impact of illegal fishing is still undetermined (Ríos-Lara et al. 2012). but publically known to occur by non-cooperative members that access the MPA's illegally without fishing permits or licenced boats. Mainly referring to undersized lobsters being caught in SK, in the MSC report (MRAG-Americas 2012, 2013), it is mentioned that: "The assessment team also recommends increasing monitoring in the boundaries of Sian Ka'an to further deter illegal fishing. "This should continue to be a matter of attention until it is ensured that illegal fishing no longer occurs. .

In SK, effort concentrates around the BA and BES bays, and is limited through concessions managed by the three registered cooperatives Vigia Chico, Cozumel and Jose Ma. Azcorra, as described in sections 1.2.2.1.1 and 1.2.2.1.1. However, areas along the southern border within SK are officially part of the concession limits pertaining to cooperative Langosteros del Caribe, which only fishes in BC. This situation has consequently left an open space for free fishers to illegally harvest in that southern portion, which in turn goes unreported in the official landing data for SK. Consequently there is currently an unestimated amount of harvesting, effort and exploitation of the southern portion of the SK

stock which needs to be controlled, monitored or at least considered in future stock assessments.

Also occurring in BC, the CONANP environmental authorities have reported an annually variable number of cases of illegal fishing, but catching fishers has been rare, resulting in a small but unknown underestimation of the exploited stock. This is because the effects of effort from illegal fishing have either been considered negligible or have been understated (Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010), but these should nevertheless be estimated and incorporated into future assessments

As both fisheries occur within the boundaries of federal marine reserves, a number of institutions are interested in the conservation and management of the lobster resource, and generally eradicating illegal fishing, by increasing patrol in the MPA's and by controlling trade and landings in the coastal areas (see Annex 12.1.). Several research studies have been produced in the region, but up until now none have estimated the biomass which is caught illegally. Nevertheless, long term time series of catch and effort data do exist for these fisheries, recorded by cooperatives and fishing authorities (Ríos-Lara et al. 2012), both for Banco Chinchorro (Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010) and Sian Ka'an (Sosa-Cordero et al. 2008, Ley-Cooper 2013, Sosa-Cordero 2014), which have shown relative stability since the nineties, in terms of total landings and relative catch rates (catch per unit of effort) in both areas.

9.3.1.1.6 Effort Limitation:

Effort limitation or input control systems consist of four elements: control on the amount and type of gear ii) constraints on the time and space, where this gear can be made use of iii) a system for managing improvements in terms of effort over time, because of technological innovation, and iv) systems for managing transferability of effort between operators (Gardner et al. 2013). An effective application of these elements could help management move towards a level of effort that approximates maximum economic yield (MEY)(Morgan et al. 2009), and certainly would be the optimum management arrangement in the SK and BC areas This is especially true if the differences in price ranges from the beginning to the end of the season were to be capitalized by implementing a MEY scheme (Ley-Cooper & Chávez 2009, Ley-Cooper 2010, Jain & Garderet 2011) based on bio-economic criteria (Caputi et al. 2008), in which seasonal dates could be modified in such a way that effort is effectively concentrated towards November –February when prices are

higher, leaving September and October as a no- take period for recruitment and growth (Ley-Cooper et al. 2014). This action would increase benefits and reduce costs in these fisheries.

Defining MEY to control effort has great potential benefit, but this is a complex task involving certain risk if there is a lack of corresponding input information and data for grounding the parameters and modelling methods which might suggest where and how effort should be limited to ensure better economic performance. As described in section 1.6.5 where modelling for MEY using FISMO was reevaluated (Ley-Cooper & Chávez 2009) we acknowledge that minimal changes in basic input data (M,F,CPUE) can considerably change outputs in simulation scenarios (E, MEY) when manipulating catch data series. The experience with BC evidenced some of the caveats of modelling for MEY if data is not empirically grounded. However, instead of moving away from determining and achieving MSY in the SK and BC fisheries, identifying faults and benefits from the latter experiences should incentivise future work to produce input data and information as a basis for modelling, resulting in more precise output scenarios, which are intended for improving effort rates, management, decision making and eventually moving towards an MSY scheme in these MPA's.

When assessing sustainability performance of SK and BC, it is worth considering a range of studies and evaluations that use different methods of analysis and modelling techniques (MRAG-Americas 2013). The literature review for BC fishery, revealed discrepancies in population parameters used for estimating exploitation rates and showed that differences resulting from distinct modelling techniques and criteria may produce inconsistent outcomes (Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010). This suggests that stakeholders, experts, managers and authorities should collaborate more in standardizing monitoring programs that produce the input data, and should carry out participative risk assessments (Fletcher 2005). As occurs in other MSC certified lobster fisheries (de Lestang et al. 2012), experts should be invited to discuss and agree on input criteria, methods for local assessment should be implemented with local consents in conjunction with peer reviewed processing of information and results from standardized data sources (Bellchambers et al. 2014). This would result in more scientifically solid evaluations and facilitate agreement on potential management strategies, that could maximize sustainability of the resource while maintaining economic benefits for the fishery (Gardner et al. 2013).

9.3.1.1.7 Recommendations for assessing and managing the population stock in deeper portion areas of BC and SK

As published in Ley-Cooper et al. (2013, 2014), a particularly relevant finding was that lobster movements and migration patterns, to and from the deep (>20 m) unfished areas outside the bays of SK, strongly affect assessment bias, and should always be considered in future stock assessments for both SK and BC areas. Stock assessment simulations must be consistent with empirical information about the local deep and shallow spatial distribution of spiny lobsters in each specific area (Lozano-Álvarez et al. 1991b, Hoenig et al. 1998, Goñi et al. 2010, Bertelsen 2013, Harford et al. 2015).

Ley-Cooper et al. (2014), state that if the fraction of the stock inhabiting the deep (>20 m) shelf or reef walls (Lozano-Álvarez et al. 1993), is smaller or larger than that predicted in population stock simulation models (Ley-Cooper & Chávez 2009, Alvarez-Flores & Sosa-Cordero 2010, Ley-Cooper et al. 2014), outputs of stock assessment may change drastically, and outcomes used for suggesting management measures may be erroneous, as migration can have a strong influence on the accuracy of assessment procedures, especially if emigration is incorrectly perceived as mortality (Goñi et al. 2010, Ley-Cooper et al. 2014, Harford et al. 2015). Modifying assumptions about semi-closed stock may affect these estimates of mortality and should therefore be considered in designs for future mark-recovery experiments (Harford et al. 2015). The mark recovery approach I used and modelled in chapters 0,6 and 7 appears robust to movement uncertainty, but places where deep water areas act as *de-facto* reserves (Lozano-Álvarez et al. 1993, Briones-Fourzán et al. 2000), such as SK and BC require tagging in both deep/unfished (>20 m) and shallow/fished (<20 m) areas to avoid estimation bias.

When modelling for stock assessments (see Chapters 0 and 6), if only a small fraction of individuals were to be estimated as inhabiting the deep (>20 m) unfished areas in BC and SK, migration bias might be small, yet this assumption has the risk of being highly uncertain and requires additional empirical investigation (Harford et al. 2015). Besides considering tag loss (Melville-Smith & Wing-Yuk 2002, González-Vicente et al. 2012), and estimating tag reporting rates, (Frusher & Hoenig 2003), when estimating fishing mortality, tagged lobsters within the fished area may be removed in three ways: natural mortality, fishing mortality, or emigration to another area; this means that using tag recoveries from only the fished area produces biased fishing mortality, unless emigration (movement between fished and unfished

areas) is accounted for (Ley-Cooper et al. 2014). If emigration is not considered this could produce underestimates of fishing mortality in the fished areas (<20 m).

If the decision to preserve the deep stock (>20 m) were to be enforced in new management terms, tagging experiments for mark-recovery will be needed for estimating stock-wide fishing mortality, as well as to indicate movement between areas, as this could produce biased estimates if movement between areas is not accounted for in the estimation procedure (see Chapters 0 and 6) (Goñi et al. 2006, Goñi et al. 2010, Ley-Cooper et al. 2014). Without any actual mark-recovery procedure there is a risk of fishing mortality estimates to be erroneous because several parameters such as natural mortality must be fixed as “true values” rather than estimated with uncertainty from auxiliary data, as currently occurs when creating models with FISMO (Ley-Cooper & Chávez 2009). If we don't incorporate movement between areas in the modelling simulations, we would essentially be performing assessment for two distinct stocks, one for which information is available (areas subject to exploitation <20 m), and one for which no information is produced (deep unfished area >20m). However, if we introduce movement estimation rates between these areas into the model, bias can be specified as related to movement rates and not misspecification of other aspects of population dynamics (Hoenig et al. 1998, Harford et al. 2015).

9.3.2 Environmental impact of fishing:

SK and BC are struggling to address the habitat and environmental impact of the fishery and sustainability issues which have not been the traditional focus of fishery management agencies. This is also the case with most other MSC certified lobster fisheries (Heupel & Auster 2013, Bellchambers et al. 2014), Ríos-Lara, 2012 #295}. Therefore, addressing the criteria and associated conditions for certification will require considerable ongoing research and assessment for these fisheries (Agnew et al. 2006, Agnew et al. 2013, MRAG-Americas 2013). The assessment team, will have to represent an experienced fishery group, in order to achieve comprehensive understanding of all aspects of the fishery (SCS 2006 , Bellchambers et al. 2014).

The relatively small scale of the lobster fisheries in BC and SK and the lack of consistent/robust information on their impact on habitat and ecosystem factors, have made the evaluation of these sustainability performance indicators a difficult task. However, these fisheries have met the MSC status requirements in this regard, as they were considered to have negligible impact on other retained non target or by-catch species, nor did they have any

impact on endangered, threatened or protected species, habitats and ecosystem components (MSC-P2) (MRAG-Americas 2012, 2013). Nevertheless, the current ongoing studies and conservation projects are not sufficient to ensure continuous monitoring of these factors, or to detect any increase in risk to benthic habitats or ecosystem from fishing activities, so certification has been conditional upon establishing a specific monitoring program for both the habitat and the ecosystem..

These fisheries are classified as small scale (Seijo 2007), and are considered to cause low environmental impact as they operate within a Biosphere Reserve that complies with a limited effort scheme (see section 9.3.1.1.6). This is mainly maintained by restricted access, controlled licencing and only allowing free diving techniques, as well as the use of casitas as a fishing gear that limits the catch to certain habitats and depths <20 m (see chapters 4,0, & 6) (Briones-Fourzán & Lozano-Álvarez 2013). However, the fact that casitas are now being proposed as apt fishing gear for BC (see Chapter 4) is a matter of to be considered in the near future, as these may cause certain changes in the ecosystem (Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2001a) and local lobsters population dynamics (Briones-Fourzán & Lozano-Álvarez 2013, Gutzler et al. 2015). This is why these matters need to be further explored with *ad hoc* on site experimental designs (see Chapter 4 and section 0 on future research and monitoring needs).

The pre-valuation hypothesis for BC is that the correct and supervised implementation of casitas will allow for free movement of lobsters between these and other natural refuges in nearby areas. This will also extend feeding ranges in neighbouring Campos, thus increasing juvenile survival rates and enhancing total stock numbers, without any considerable negative environmental impact (see Chapter 4) (Briones-Fourzán et al. 2007, Briones-Fourzán & Lozano-Álvarez 2013). It is assumed that casitas are known to: 1) alleviate demographic bottlenecks by mitigating a limited supply of crevice habitat and reducing intraspecific competition for shelter; 2) allow lobsters to take advantage of abundant food resources over large open areas where predators would normally prevent them from doing so; and 3) increase the potential for gregariousness, thus extending the benefits of anti-predator group defence to lobsters of all sizes that occupy casitas (Eggleston et al. 1990, Eggleston & Lipcius 1992, Sosa-Cordero et al. 1998, Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007).

The field work carried out during the development of this thesis (Chapters 4 & 0) (Ley-Cooper et al. 2011, Ley-Cooper et al. 2013) confirmed findings indicated by previous studies regarding the relatively low impact that casitas have on the seagrass habitats where they are placed (Sosa-Cordero et al. 1998, Briones-Fourzán et al. 2000, Briones-Fourzán & Lozano-Álvarez 2013). Minimal area coverage is shaded by each casita (1.5- 2 m²), resulting in low density (1 casita every 50 m²), within the quadric arrangement of the traditional SK Campo systems (see Figure 1-7) (Briones-Fourzán et al. 2007, Briones-Fourzán & Lozano-Álvarez 2013), temporarily inhibiting growth of surface grass sprouts directly underneath casitas, yet allowing root survival so that sprouts will regrow, as soon as casitas are removed.

Feeding traits and food ingestion patterns among *P. argus* don't show significant differences between casitas and natural refuge sites (Gutzler et al. 2015), likewise the stepping stones provided by the casitas distribute the foraging activity of lobsters over wider areas and do not appear to significantly impact the abundance and diversity of the small invertebrates that constitute their prey (Briones-Fourzán & Lozano-Álvarez 2013). This implies that the impact, attributed to the use of casitas, seems minimal on other non-target species on which *P. argus* lobsters feed.

Many studies have shown that casitas increase production of lobster biomass primarily by enhancing survival of the juveniles (detailed in Chapter 4) (Sosa-Cordero et al. 1998, Briones-Fourzán et al. 2007, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013), thus disputing the theory of casitas being “ecological death traps” as recently suggested by Gutzler et al. (2015). Although the study by Gutzler et al. (2015) is interesting in this regard, there are certain critical caveats in the methodologies used for their experimental design as: a) juvenile *P. argus* lobsters were studied in a very low density casita arrangement (16 total) which is very dissimilar to SK; b) the study was established mainly on sandy areas and so called “casitas” had very different characteristics and designs to those used in SK; c) when tethered, lobsters were wrongly located near the entrance and not directly underneath casitas, which tends to induce attempts to escape casitas as a reaction; and d) when lobsters were manipulated for the experiment, it is not clear in the methodology whether lobsters were previously removed from other areas distant from casitas, hence the possibility of prompting homing and miss-orientation behaviour as a reaction to being transposed (Lozano-Álvarez et al. 2002, Bertelsen 2013, Ley-Cooper et al. 2013) and d) estimating survival and predicting increased natural mortality under casitas by using tethering methods is questionable, as it is unlikely that lobsters would mimic “normal” social defence

behaviour (Herrnkind et al. 2001 , Childress & Steven 2006). Furthermore, tethering is likely to increase lobsters' vulnerability to predators when attempting to move longer distances between different refuges or for feeding purposes (Bertelsen 2013). As shown in this study, long distance movements between casitas and Campos are likely to occur after manipulating lobsters, so natural mortality would be better assessed using a non- retentive method such as T bar tagging, especially when transposing them from natural refuges to casitas (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014). For these reasons, the proposal for installing casitas to enhance survival of juvenile lobsters and reduce pressure on natural refuge such as the reef ecosystems is sustained by this thesis, and is considered to be an alternative means for reducing the fishery's impact on natural habitat/reefs.

In both MPA's the use of lobster traps/pots as fishing gears is not permitted, which diminishes the direct impact of by-catch. Nets were not originally considered in the pre-assessment process for declaring these fisheries as sustainable (MRAG-Americas 2012), and in 2013 it was suggested that there should be a traceability system put in place to guarantee lobsters caught with nets were not mixed in with those that were certified as sustainable (MRAG-Americas 2013). In the latest MSC assessment meeting held on May 2015, fishers from JMA cooperative and authorities self-proclaimed to have totally eliminated the use of nets near the BES-SK.

In BC and SK Mexico, the fishing industry, scientists and managers have had no prior experience with certification and thus have limited understanding of the requirements; this was also the case with other lobster fisheries (Phillips et al. 2003b, Bellchambers et al. 2014). The information available for our case study has revealed a number of gaps in the data (MRAG-Americas 2013). While each fishery is individually assessed according to its particular circumstances and requirements, there are a number of similarities between the different lobster fisheries around the world that enable comparisons between independent assessments, despite differences in the units of certification (i.e. species, location and gear). There are common areas of weaknesses illustrated by the conditions placed on each fishery. The exchange between experts to transfer knowledge regarding methods for evaluation strongly benefits assessments (Bellchambers et al. 2014), and helps to overcome any shortcomings, as has been the case when applying modelling methods for assessing the *P. argus* fishery in SK and BC which originated in the *P. cygnus* fishery (Ley-Cooper et al. 2014).

9.3.2.1.1 Recommendations for risk assessment

While including stakeholder participation, regular reviews of identified risks are important to ensure that changes in risks are recognized and that improved knowledge and research are accurately reflected in future assessments. Risk assessments have been instrumental in addressing most conditions implemented in order to attain sustainability in the case of other lobster fisheries (Bellchambers et al. 2014), Fletcher, 2005 #316}. These assessments provided useful examples for Mexico. The fishery cooperatives in BC and SK need managers and scientists with a sound understanding of the potential and ongoing risks in the fishery, as well as knowledge of relevant data and useful strategies for addressing identified risks. A robust scientifically-defensible, expert based risk assessment must provide a transparent framework that enables stakeholders to participate in relevant issues. This risk assessment should be seen as an opportunity to allow the efficient allocation of resources to future management and/or monitoring, according to risk (see section 0)(Fletcher 2005, Bellchambers et al. 2014).

As has occurred in other lobster fisheries, including *P. interruptus* in Baja and *P. cygnus* in Australia (SCS 2013), obligatory understanding of the effects of fishing effort on the different benthic habitats will most probably be established as a condition for continued MSC certification. Therefore, these criteria should be established for future strategic research plans, which in turn should be based on environmental risk assessments (ERA). As suggested by (Fletcher 2005), the ERA should involve examination of the sources of potential risk (issue identification), the potential consequences (impacts) associated with each issue and the likelihood (probability) of a particular level of consequence actually occurring. . This means that each identified issue would be allocated a risk level used to determine the degree of management response required. Issues representing moderate or above risks will require additional management responses, possibly involving additional research (Fletcher 2005, Bellchambers et al. 2014).

Although casitas as fishing gear may currently be considered to have a low environmental impact on habitat (Briones-Fourzán & Lozano-Álvarez 2001a, Briones-Fourzán et al. 2007), and are at present not a condition for continued certification of the SK and BC fishery (MRAG-Americas 2013), quantitative data is required to evaluate the physical impacts of the fisheries on all habitats where fishing occurs and where gears (i.e. casitas) are or will be placed (Briones-Fourzán & Lozano-Álvarez 2013). This quantitative

data will enable monitoring of the environmental impact of the casitas and their potential effects on fishery structure, as well as on lobster population dynamics.

As in most other sites where *P. argus* is distributed around the Caribbean (Behringer et al. 2011), the presence of Pav1 virus disease in the SK and BC populations could potentially represent a risk for the local populations, and levels of prevalence needs to be further assessed and monitored in the near future (Ramírez-Estévez et al. 2010, Candia-Zulbarán et al. 2012).

9.3.2.1.2 Recommendations for Reporting and Monitoring

Certification assessment teams do not normally have the resources to conduct independent data analysis (Phillips et al. 2003b),(MRAG-Americas 2013). So that the MSC certification of the BC and SK fishery can continue, it is recommended that a number of formal reporting and monitoring systems be implemented, and that data be presented in a more structured format. A key component to improve this process is the development of a comprehensive Principle 2- P2 yearly summary document that provides a synthesis of all research relevant to P2. Efforts from academic institutions, government agencies, and NGO's have been working semi-independently on certain components such as creating habitat maps and , coral reef assessments, *Acropora Palmata* restoration (Alianza-Kanan-Kay 2015). However, an integrated report of P2 should include outputs of ecological risk assessments, summaries of historical peer-reviewed and unpublished papers and reports, analysis of historical datasets and updates of current and ongoing research, which could follow a similar protocol to the Fishery Assessment Methodology (FAM) used in the Western Australian *Panulirus cygnus* fishery. Reports should be as comprehensive as possible and include monitoring of general environmental and habitat factors such as those previously mentioned (also see details in section 0). Additionally, identifying the risks that Pav1 virus may represent in the long run for the local lobster populations should be incorporated into the report (Ramírez-Estévez et al. 2010, Candia-Zulbarán et al. 2012).

9.3.3 Effective management

Both reserves have scored particularly well when assessment is made of the SK and BC fisheries and when adherence to the requirements of the management system is addressed. Moreover, as regards the extent of awareness of Performance Indicators, both reserves have scored particularly well; the components and hierarchy of the management system for Mexican fisheries and for the SK and BC lobster fisheries have been considered to

be well defined and well understood (MRAG-Americas 2012). The management system includes regulations and enforcement at the federal level (Ríos-Lara et al. 2007) and additional measures at the cooperative and at the MPA's reserve levels (INE-SEMARNAP 2000, CONANP 2007). The fishery participants in SK and BC have displayed a high level of responsibility and there are not many compliance issues, as acknowledged by several authors (Seijo 2007, Sosa-Cordero et al. 2008, Alvarez-Flores & Sosa-Cordero 2010, Conrad & Danoff-Burg 2011, Gardner et al. 2013). Most participants in the fishery were reported to be members of cooperatives, and comply with regulations by engaging in sustainable fishery practices. There are a few isolated illegal fishing reports, where a varying number of prosecutions occur each year, and are a focus of attention for the inter-institutional management plan involving fishing and environmental authorities (see section 9.3.1.1.2).

Sophisticated features of modern fisheries management such as quantitatively based decision rules occurring in other lobster fisheries (Gardner et al. 2013, Penn et al. 2015), are lacking in the Mexican lobster fisheries in general, and specifically for SK and BC. This is partially because of the unknown size of the stock(s), uncertainties in the recruitment processes, and the reliance on a system based on fishing rights and concessions, in which it is simply assumed that fishers organized in cooperatives are able to adapt fishing effort when changes in the resource status occur (Ríos-Lara et al. 2012).

Certification has been conditional on ratifying a draft management plan available for BC (Alvarez-Flores & Sosa-Cordero 2010) and developing another draft management plan for SK (MRAG-Americas 2013). The fisheries are still lacking fishery-specific objectives within a local management plan. Defining a precautionary approach to the decision-making process by establishing Harvest Control Rules (HCR's) is still lacking. In 2015 the scientific community has held some meetings in this regard, yet nothing has yet been put in paper. Both local management plans would need to be framed within the context of the regional lobster management plan (Ríos-Lara et al. 2012), and approved by fishing authorities, so that they could be officially implemented and recognized by all stakeholders. This requires the willingness to promote institutional collaboration between the cooperatives, governmental agencies and research institutions which own the data, so that research can be carried out and monitoring projects developed. These would be the main components to be offered in support of local management plans for certification. Ideas for how this support for certification could be developed are suggested in the Future Research and Monitoring section 10 of this thesis.

A positive aspect of the MSC and Chakay ecolabelling initiatives is that they provide performance indicators and criteria to managers and assessors, along with an accurate and comprehensive understanding of the fishery, thus reducing the likelihood of gaps in available information (Marine Stewardship Council 2010). Moreover, these ecolabelling initiatives highlight areas that may require additional data analysis, should information be inadequate or not accurately reflect the real risks and gaps (Bellchambers et al. 2014). Herein lays the importance of a majority of stakeholders backing the certification process ahead of time, while reaching agreement on potential risks and solutions prior to evaluation periods.

Effective evaluations require technical knowledge and data (Ward & Phillips 2010, Pérez-Ramírez et al. 2012b), preparation of documents for assessment and a comprehensive understanding of the SK and BC fishery. However, if only opinions of local experts are considered this may result in motivational biases due to the alignment of individuals or agencies to a particular political or funding agenda (Bellchambers et al. 2014). The formation of an Fishing Advisory Group, comprised of local, national and international experts, may minimise potential biases, because the group can provide a broader perspective when identifying and addressing risks in the fishery, based on their experience in other fisheries and research reviews (Bellchambers et al. 2014). Budget is an issue, but the idea would be that these tasks could be inserted into the existing institutions agenda. Establishing a strategic framework whereby the components inform each other in a transparent and structured fashion is a key element, because fisheries are not static but change with technological advances such as the implementation of casitas in BC; market demands such as the preference for live lobster; and management changes such as the establishment of no take zones (refugios pesqueros) (Ley-Cooper 2009). A defined framework will provide a clear pathway for identifying and addressing changes in risk.

A good example of effective management has been the successful change in fishing gears and practices in BC in 2009, since the use of gaff/hooks has almost been completely replaced by snare loops for catching live lobsters in BC (Ley-Cooper & Garcia-Rivas 2009). Market preferences have been critical in promoting this change because there is an increased sales price for whole live lobsters compared to lobster tails (Ley-Cooper 2010). The most positive outcome resulting from this change in fishing practices has been the increased selectivity of non-egg bearing females and legal sized lobsters, as lobsters are no longer killed with hooks underwater. When caught with snares, the lobsters can be freed if misjudging the size or are egg bearing (Ley-Cooper 2010). Empirical observations indicate

that there is an increased level of difficulty for catching lobsters alive by having to free-dive under cryptic refuges and coral structures using these snares, which has probably reduced fishing effectivity in terms of the time invested underwater, which in turn could considerably reduce catchability and the catch per unit of fishing effort, yet this is only a hypothesis that must be assessed in the near future.

9.3.3.1.1 Recommendation strategies for management and for mitigating risk

The potential ecological impact of lobster fishing with nets in southern SK was identified as a moderate risk in the 2013 MSC surveillance visit (MRAG-Americas 2013, Bellchambers et al. 2014), yet according to fishers from the JMA cooperative in BES-SK and environmental authorities nets are no longer in use as from the start of in 2015. This recent example of eliminating the use of nets is an indication of the willingness that stakeholders have to mitigate risk in these fisheries, and a result of negotiation incorporating fishers in the decision process.

The introduction of casitas into Banco Chinchorro (Ley-Cooper et al. 2011) (see chapter 4) needs to be closely assessed and supervised by experts (Briones-Fourzán & Lozano-Álvarez 2013), so that the potential impacts of their implementation along with risk factors can be measured and assessed from the beginning (Briones-Fourzán et al. 2007),(Ramírez-Estévez et al. 2010)) in case the initiative represents some sort of risk to the environment, lobster population, or other species (Gutzler et al. 2015).

As previously mentioned in section 9.3.2.1.1, an advisory group of scientists and managers, should be established to determine: the effects of current fishing practices on the ecosystem and habitats which have been identified as possible risks and to provide expertise for ERAs, thus forming a critical mass to framework and provide guidance through the development, and regular review of the strategic research plan. The latter and a P2 evaluation document should all become Key elements for achieving sustainability and dealing with the conditions put in place by the MSC's certification process (see section 0)..

Research needs to occur in a structured manner, the advisory group must devise a strategic plan to deepen understanding of the effects of current fishing practices on the ecosystem (i.e. implementation of casitas). Assessments should include habitat and stock(s) found in the deeper water (>20 m) (Ley-Cooper et al. 2014), and fishing effort exerted on other species for “self-consumption” (i.e. groupers, snappers, rays and conch) as these may be protected or considered to be by-catch once a certain volume is reached.

9.3.3.1.2 Recommendations on Harvest control rules (HCR's):

In SK and BC biological reference points and control rules are not yet well defined. It is however recognized that at the local level, fishing cooperatives historically have had control mechanisms to limit catch and effort, and these traditional values and empirical control measures have apparently been effective in maintaining the stocks at relatively stable and sustainable levels (see Chapters 5, 6, 7 and 8) (Sosa-Cordero et al. 2008, Briones-Fourzán & Lozano-Álvarez 2013, Gardner et al. 2013), nevertheless these traditional methods may not be sufficient in the long term.

The responsibility of scientists, managers and stakeholders to mitigate the unsustainability of marine fisheries is complex (Caddy & Seijo 2005), and the regional connectivity of *P. argus* as a Meta-population implies that there should be a shared obligation for conservation of the breeding stocks to ensure recruitment throughout the entire Mesoamerican Reef (Seijo 2007). The need for international cooperation at a regional scale is important locally, as source populations that export larvae into SK and BC are likely to be found elsewhere beyond Mexican borders (Briones-Fourzán et al. 2008, Truelove et al. 2014). Hence if the SK and BC population(s) are highly dependent on external populations for larval influx and settlement (Butler et al. 2011, Muhling et al. 2013), local declining stock sizes may not necessarily be induced or controlled only by the local fishing practices; so in the face of the possibility of approaching limit reference points in recruitment, the most immediate task is to develop local harvest control rules that are able to respond to changes in sustainability of the stock status, while ensuring that the exploitation rates are reduced or controlled if required.

To establish catch and effort limits as well as harvest control rules (HCR's) in the SK and BC fisheries, the total stock biomass should be considered, this must also include lobsters found in unfished areas (>20 m) (see section 9.3.1.1.7). The deep areas (>20 m) contain a considerable proportion of the population that escapes the fishery, and are key for recruiting adult lobsters into the areas subject to exploitation (Ley-Cooper et al. 2014), so lack of information in this regard may impede accurate estimates of fishing mortality and abundance of total stock. Precise determination of these factors is necessary for evaluating the stock which is subject to fishing exploitation rates (Ley-Cooper et al. 2013), and hence for establishing possible HCR's.

Differences in size structure between fished and unfished areas (>20 m) should be monitored, for ground truthing the local population parameters needed for feeding the simulations and stock assessment models. These should be revalidated yearly to avoid parameter misspecification (Ley-Cooper et al. 2013,2014). Size based or density dependent movements due to emigration or ontogenic shifts between essential habitats (Acosta & Robertson 2003, Bertelsen 2013, Briones-Fourzán & Lozano-Álvarez 2013), could have implications for the movement patterns predicted in the models (Harford et al. 2015). Movements may also be prompted by environmental factors such as cold fronts/Nortes (García et al. 1991), which affect catch rates and relative abundance, so these changes must also be monitored to better estimate the effects that migration patterns may have on exploitation rates (see Chapter 7).

Uncertainty regarding abundance/biomass of lobsters in the deep unfished areas (>20 m), evidences the need to preserve and assess these areas using appropriate modelling techniques and experimental designs for tagging, to eventually assess local natural mortality rates (M), as well as fishing mortality rates (F) in both fished and unfished areas, and to establish possible biological reference points related to protection of the spawning stock (Ley-Cooper et al. 2014). In areas where fishing mortality is high, determining stock status that includes nearby no-take areas and monitors dispersal characteristics within these areas may be essential for determining the long-term performance of management practices (Bevacqua et al. 2010, Ley-Cooper et al. 2014, Harford et al. 2015). Adequate measures for these parameters and estimates of exploitation rates could then be used to determine more precise Harvest Control Rules (HCR's).

A previously proposed HCR is to decrease pressure on the southern coral banks in BC, and could be implemented in parallel to the initiative of casita instalment in northern areas of BC (Ley-Cooper et al. 2011)(see Chapter 4).

9.3.3.1.3 Declaring the deep unfished area (>20 m) a non-take zone (refugio pesquero)

As discussed throughout the thesis and detailed in Chapter 6, the < 20 m depth fishing limit in BES-SK helps a significant proportion of the deep adult stock escape the fishery in the deep (>20 m),and progressively recruits lobsters into the shallow areas subject to exploitation. Hence these could be “unofficially” described as *de-facto* un-fished areas that enhance the fishery (Ley-Cooper et al. 2014), otherwise known as No Take Zones.

Information produced by this study could provide the expert advisory group with a technical basis to further elaborate this idea (Ley-Cooper et al. 2013, Ley-Cooper et al. 2014), and establishing a significant strip of deep water as No Take Zone “refugios pesqueros” ranging from 20 to 100 m depth in order to preserve the *P. argus* reproductive stock. This way the deep breeding stock would not be subject to exploitation even if future fishing practices were to change, or new gears were to be introduced (i.e. SCUBA, pots and traps). This could be an optimal HCR to be officially put in place in these and other MPA’s in the MBRS, which would benefit the breeding stock component of the local populations, and help maintain larval export and recruitment levels throughout the distribution of the *P. argus* species meta-population.

9.3.3.1.4 Additional seasonal effort limits

The premise of a semi self-contained stock management of the effort in SK and BC seems reasonable, and specific considerations regarding the virtual boundaries and limits to the benthic, post-settlement “standing” populations in BC and SK are discussed in detail in section (9.3.1.1.1). Based on the former premise management could also be improved by increasing temporal effort limits on these fisheries to achieve a Maximum Economic Yield (MEY) (Gardner et al. 2013, Penn et al. 2015).

A way of optimizing the fishery and defining measures based on Maximum Economic Yield criteria is to include additional short season closures (Morgan et al. 2009), preferably throughout the September and October months when lobster are scarce and prices are low. In Q. R., the lowest price and demand for lobster occurs during this period which is the low season for tourism and which happens to coincide with a decrease in catch rates, historically observed in these fisheries (Chapter 7). The second recruitment peak occurs in late autumn and winter (late October and November), which is presumably induced by Nortes that generate lobster movements from the deep unfished areas (Ley-Cooper et al. 2014), and cause movement of juvenile cohorts from within the shallows areas (Ley-Cooper et al. 2013). Thus a short time closure occurring in September and October would most probably reduce effort and costs for fishing operations and would allow for an increase in abundance/growth in shallow areas (<20 m) normally subject to fishing. Studies based on bio-economic modelling should analyse and propose the precise timing for these temporary closures to occur (Penn et al. 2015), The proposal to carrying out short term closures during September/October is bound to increase catch rates and economic yields in the December to

February period, when lobster fisheries have the second recruitment peak (Ley-Cooper et al. 2013) and prices are at their highest value (Jain & Garderet 2011).

Fishery stakeholders that work in BC and SK have appreciated the potential economic benefits derived from adding value to live lobsters that are fished in a sustainable manner, and consequently have adopted most of the scientific recommendations and management suggestions for changes in technology and fishing practices (Ley-Cooper & Garcia-Rivas 2009, Ley-Cooper & Quintanar-Guadarrama 2010, Jain & Garderet 2011). Applying the Chakay rules of use (IMPI 2009) and following the MSC protocol (Marine Stewardship Council 2010) will eventually require having formal scientific risk assessments on a yearly basis (Fletcher 2005, Bellchambers et al. 2014), and a revaluation for certification every five years (MRAG-Americas 2013). This thesis has made many suggestions in this regard, and has highlighted both advantages and disadvantages associated with the implementation of the eco-labels. Regardless of whether stakeholders decide to continue or not with the current ecolabelling schemes in the near future, studies of this nature can help for developing further and more effective management strategies. The use of bio-economic criteria to maximize benefits and balance fishing effort with yield is recommended (Puga et al. 2005, Ley-Cooper & Chávez 2009, Morgan et al. 2009, Gardner et al. 2013, Penn et al. 2015), as well as the adoption of appropriate harvest control rules based on empirical scientific evidence (Ley-Cooper et al. 2013, 2014), given that these may optimize exploitation and safeguard the long term sustainability of these fisheries.

10 Future research and monitoring needs

As part of the five year working plan for the ongoing MSC certification and Chakay ecolabelling schemes, stakeholders including fisher cooperatives, fishery and environmental management agencies, NGO's and research institutions have committed themselves to developing a permanent monitoring and research program (MRAG-Americas 2013), and to periodically assess the status of these fisheries. However a formal proposal needs to be designed discussed and embraced by all stakeholders working in this fishery, since a program of this nature has historically been limited by the lack of staff and economic resources assigned for this purpose. A conclusion reached as a result of this thesis is that fisheries (CONAPESCA-INAPESCA) and environmental (SEMARNAT-CONANP) management agencies should coordinate actions in this regard, with technical support from academic institutions working in these areas (e.g. UNAM, CURTIN, ECOSUR, CINVESTAV, UQR., IPN), and from NGO's (e.g. RAZONATURA, COBI, WWF, TNC, FMCN, MAR) as they all may share common goals and objectives that could help achieve sustainability of these fisheries. For this purpose, as the last section of this thesis I have produced Table 10-1 which summarizes and outlines some suggestions made throughout the previous chapters..

Collectively developing integrated monitoring and assessment frameworks will encourage scientists and managers to evaluate, analyse and gather data in ways which they will more likely achieve management objectives. To evaluate the effectiveness of marine reserves and no take zones as fishery management tools, a comprehensive approach and data rich assessments and are required. A monitoring program for SK and BC reserves could complement the general framework which has been structured within the lobster fishery management plan for the whole Yucatan peninsula (see Ríos-Lara et al. (2012)). Collection of more detailed fishery based data can expand on the currently succinct log book information. Moreover, the generation of fishery independent data should enrich the research schemes and help improve future assessments of these fisheries (see section 9.3.3) as indicated in the following Table 10-1:

Table 10-1: Shows the suggestions for future research and monitoring actions for the *P. argus* fishery in the BC and SK Biosphere Reserves (central 2nd column); Order of priorities proposed (3rd Column); and references to sections in this thesis (4th right hand column) based on the existing framework of the lobster management Plan for the Yucatan Peninsula (1st left hand column)

| <p>Current Management plan research program (Ríos-Lara et al. 2012).</p> | <p>Recommendations for research, monitoring and research complementary information suggested for BC and SK (see section 9.3.3)</p> | <p>Order Of Priority as suggested by Ley-Cooper, K</p> | <p>Reference section(s) in thesis</p> |
|--|--|---|--|
| <p>Create a researcher network group for studying lobsters including fishery science, technology, social and economic aspects. On a permanent basis.</p> | <ul style="list-style-type: none"> To facilitate, develop and eventually implement a permanent and successful monitoring program, it is suggested to carry out a series of participatory workshops involving most stakeholders of the SK and BC lobster fishery, where fishers' perceptions should be considered when establishing priorities. Participants should determine and agree to the terms and conditions of this monitoring program, which previously should be outlined by an expert committee composed of managers, research scientists and technicians working in the field. The application of a qualitative risk assessment methodology to prioritize issues for the management of these fisheries is also recommended | <p>1</p> | <p>Sections 9.3.1.1.6; 9.3.2.1.1; 9.3.3.1.1</p> |
| <p>Evaluation studies of the lobster populations, to determine the biomass</p> | <ul style="list-style-type: none"> The management “zones” as they currently stand should be reclassified to be more specifically based on the local MPA’s management criteria. A reevaluation of the lobster management units, should | <p>2</p> | <p>Chapters: (5, 6 and 7)</p> <p>Sections:</p> |

| | | | |
|--|--|-----------------|---|
| <p>and effort characterized by zones in the Gulf of Mexico and Mexican Caribbean. On a permanent basis.</p> | <p>consider local population dynamics, and re-determine the stock's current boundaries, whilst taking into account bathymetric, habitat, ecosystem, and oceanographic factors to define these.</p> <ul style="list-style-type: none"> • The three areas: i) BC, ii) BA and iii) BES in SK should be assessed separately as semi-independent units for estimating exploitation rates, but must consider that there is a level of adult exchange/migration between the bays and between shallow and unfished deep stocks. Hence movement rates and connectivity should be further evaluated and incorporated into the future studies and stock assessment modelling of these fisheries. • Apply or re-validate the existing modelling techniques for analysis of the lobster populations, in order to maximize sustainability and bio-economic benefits at SK and BC fisheries. • Determine and assess biological reference points. | | <p>6.2.4;6.2.6; 6.3.2;6.3.4; 9.3.1.1.1; 9.3.1.1.6; 9.3.3.1.2</p> |
| <p>Studies for evaluating Catch and effort analyses to determine CPUE per zone. On a permanent basis.</p> <p>(Note: Fishery dependent data is obtained from landing records at the coast ranging from weekly to monthly periods)</p> | <ul style="list-style-type: none"> • I recommend log book records to include daily catch rates instead of weekly ones, as well as details on number of boats, number of fishers and the time spent fishing and searching for lobsters. This should include GPS positioning of the fished areas, and/or randomly tracing the trajectory of the fleet for assessing lobster spatial distribution, estimating relative abundance, and assessing the potential impact of the fishery on specific habitats • A system for updating, verifying and crosslinking the official listings of cooperative catch numbers against individual boat catch records. | <p>3</p> | <p>Section 9.3.1.1.2;9.3.1.1.3;</p> |
| <p>Evaluate the effort levels which allow for increasing profits in the different “zones”.</p> | <ul style="list-style-type: none"> • Estimate the illegal catch rates and impact on the stocks | <p>4</p> | <p>Section 9.3.1.1.6;</p> |

| | | | |
|--|---|-----------|--|
| Assessment of illegal fishing. Long term basis. | | 17 | Section 9.3.1.1.5; |
| Update of studies regarding reproduction in the Yucatan and Mexican Caribbean. On a medium term basis. | <ul style="list-style-type: none"> • Biometric data should be collected at the 3 different sites BC, BA and BES, to assess size structure and characteristics of the local population(s) in each MPA on a monthly basis. • Data should include the size, sex, state of sexual maturity, and presence of clinical signs of PAV1 virus disease to understand current status and trends in each area. | 5 | Section 9.3.2.1.1 and 9.3.2.1.2 |
| Identify the presence of (PAV1) in lobster populations | | 7 | |
| Characterize preferential habitats for lobster, and identify critical areas in the different fishing zones. On a short term basis. | <ul style="list-style-type: none"> • Conduct classification of satellite/aerial imagery including analysis and ground truthing for habitat mapping, and monitoring the changes and impact of the fishery on these biosphere reserves for the 3 sites BA, BES and BC. • Install temperature and salinity data loggers in different locations with distinct habitats (i.e. reef patches and seagrass) and on casitas in within SK and BC. • Carry out diver- based band transects, tow video and photo transects, and remote under water video assessments for monitoring of fish and other marine fauna populations associated to the ecosystem. After establishing a baseline and choosing the sites these should be re assessed at least every 5 years. | 13 | Chapter 7 Sections: 7.2.3; 9.3.1.1.1; & 9.3.2 |
| Evaluate the impact of environmental factors on lobster distribution and abundance | | 14 | Sections: 7.4; 9.3.2 |
| Generate indexes for evaluating the impact of the fishery on other crustacean, molluscs and fish populations | | 15 | Section 9.3.2 |
| Assess the temporary and spatial distribution of lobsters in the deep and shallow areas. On | <ul style="list-style-type: none"> • Initiate biannual fishery independent surveys by using mark-recapture techniques at different sites and depths within and beyond the commonly fished | 6 | Section 9.3.1.1.7 |

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| a medium term basis. | <p>areas, considering the 20 m depth limit as a borderline at the three sites BES, BA and BC.</p> <ul style="list-style-type: none"> Assess the potential bio-economic impact of implementing new harvest control rules and alternative management measures, such as establishing maximum size limits, or total allowable catch (TAC) with individual transferrable quotas (ITQ). | | |
| Study the effects of using nets/pots on the reproductive stock | | 16 | Section 9.3.1.1.7; 9.3.3.1.3 |
| Study connectivity between the deep reproductive stock in the Yucatan and North-eastern stock in Quintana Roo. Short term. | <ul style="list-style-type: none"> The SK and BC stocks should be assessed with regard to the southern and northern Quintana Roo. stocks/populations including Mahahual/Xcalak areas in the south and Tulum/Akumal areas in the north. As part of the fishery independent surveys, tagging studies with an <i>ad hoc</i> design for this purpose should be extended to both biosphere Reserves. | 11 | Sections: 9.3.1.1.6; 9.3.3.1.3 |
| Asses the connectivity between lobster sub-populations at a regional level. Short term. | <ul style="list-style-type: none"> To investigate puerulus recruitment by installing and assessing catches from collectors at SK and BC in order to monitor and address the potential risk of a reduced larval influx which could affect both fisheries, and correlate possible variations with changes occurring on climatic factors (i.e. temperature and salinity), as well as local and regional oceanographic features. For local and regional population genetic analysis, and definition of the biological and stock management units; lobster samples (i.e. legs) need to be collected, including all sizes representing different age groups, ranging from pueruli, to large adults during a period of 3-5 years, and preferably coupled with oceanographic and hydrodynamic data. All MBRS countries including Cuba should be sampled and considered for a comprehensive study. | 12 | Sections: 9.3.1.1.1;9.3.1.1.1 |

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|--|--|------------------|--|
| <p>Evaluate advantages and disadvantages of introducing artificial refuges into the natural environments, and determine the zones where these can potentially be placed.</p> | <ul style="list-style-type: none"> • A comprehensive analysis of data collected during and after this study is yet to be completed to assess the impact and implementation of casitas in BC. It should evaluate the impact of casitas from an ecological/habitat perspective; study recruitment and mortality at all stages from juvenile to adult lobsters; and assess the effects because potential stock enhancement deviates from bio-economic perspective. | <p>8</p> | <p>Chapter4 Section 9.3.2</p> |
| <p>Periodically assess and study fishers social and economic conditions in lobster fishing communities in the Gulf of México and Mexican Caribbean</p> | <ul style="list-style-type: none"> • Assess added value derived from the Chakay/MSC ecolabelling schemes which recognize sustainable practices. • Apply existing technology (i.e. holding tanks, chillers, packaging techniques) for reducing mortality for live lobster transport to China, Europe and markets which recognize ecolabelling efforts, and the quality of the product obtained in BC and SK. | <p>9</p> | <p>Chapter 8 and Sections: 0; 8.5; 9.1.1</p> |
| <p>Assess alternatives for new marketing strategies</p> | | <p>10</p> | <p>Sections: 8.1, 8.3,8.4</p> |

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12 APPENDIX

12.1 Mexican Fisheries Management, instruments, and legal Definitions selected and summarized for this study

The agency responsible for fisheries management, monitoring and enforcement is the National Commission of Aquaculture and Fisheries (Comisión Nacional de Acuacultura y Pesca-CONAPESCA), which directly depends on the Secretariat of Agriculture, Fisheries and Live Stock (CONAPESCA-SAGARPA) and has delegations (Subdelegación de pesca) represented in each state (e.g. Q. R. and Yucatan) managed under the Federal law and the Mexican Constitution, as is all legislation that applies to Mexican marine resources within the territory along the Pacific and Atlantic coasts. México subscribes to several international agreements and has developed national legal frameworks which make it illegal to catch or kill endangered, threatened or protected-ETP species. The relevant official documents include: the Political Constitution of Mexican United States; General Law for Environmental Protection and Ecological Balance (LGEEPA) and its regulations on natural protected areas; General Law for Wildlife (Ley General de Vida Silvestre); General Law for Sustainable Development on Forestry and its regulations; Fisheries Law and its regulations; Federal Penal Code; and Official Mexican Technical Regulations (NOMs).

The following definitions have been placed in alphabetical order for simplicity:

Authorities involved: These will be defined as all those agencies, committees, institutions Federal, State and municipal entities related in some way to the lobster fishery, harvesting, processing, or commercialization of the *P. argus Panulirus argus*, including but not limiting to the following list with the corresponding acronym: Secretaría de Agricultura, Ganadería, Desarrollo Social, Pesca y Alimentación (CONAPESCA-SAGARPA), Comisión Nacional de Acuacultura y Pesca (CONAPESCA-SAGARPA), Consejo Nacional de Pesca y Acuacultura o el Consejo Estatal, Instituto Nacional de Pesca (INAPESCA), el Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria (SENASICA), Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad (CONABIO), Procuraduría Federal de protección al Ambiente (PROFEPA), Comisión Nacional de Áreas Naturales Protegidas, (CONANP), la Secretaría de Marina (SM) y Secretaría de Economía (SE), Instituto Mexicano de la Propiedad Industrial (IMPI), Secretaria Estatal de Desarrollo Económico (SEDE).

Banco Chinchorro: Natural Protected area created by Presidential decree on the 19th of July 1996 with a category of Biosphere Reserve, within the State of Quintana Roo., with the surface area and locality further described in the area of study

Carta Nacional Pesquera: Fisheries Regulation modified in September 1999, gave rise to the National Fisheries Chart (Carta Nacional Pesquera, CNP) elaborated by the INP (currently known as INAPESCA) and first published as an Official Decree in 2000. It is now also an implemented instrument in Mexican fisheries management with the characteristic that it is updated regularly and is a binding character that must be considered in the process of decision making by management authorities. Its main function is defining levels of fishing effort applicable to species and groups of species in specific areas providing guidelines, strategies and provisions for conservation, protection, restoration and management of aquatic resources that could affect their habitat and ecosystems.

In the version subscribed under the date of August 2006 which is still valid to date, this document presents two main elements to be considered: 1) to broadening of the concessions areas to the isobath of 100 m deep and 2) that a program should be created in order to minimize the fishing effort until reaching the “Optimum Yield”. This opens the doors to alternative management schemes for “maintaining and rehabilitating stocks” in each of the functional regional stock units. This instrument named “La Carta” indicates that fishing effort should not increase, and therefore no additional fishing permits should be allowed. It also orders the protection of settlement and development of juveniles and calls them critical areas. It is important to highlight that this instrument seems to refer to the whole state of Quintana Roo as “a fishing Unit”. This includes the North and North-eastern part of the state where the fisheries have been documented as being overexploited, indicating that fishing mortality in 2006 for the whole state was four times above the optimum, whilst the central and southern zone where Sian Ka’an and Chinchorro have been considered to be “stable”. In any case it indicates that fishing effort should not be increased.

Concession: These are authorized by (CONAPESCA-SAGARPA), to one or several Cooperatives (Sociedades Cooperativas de Producción Pesquera (SCPP)), with which all licenced activities such as fishing and harvesting of Spiny lobster *Panulirus argus* are conceded within a specific area in a polygon authorized for that purpose. These include the rules and conditions which limit the maximum number of fishers and boats in a given list which should be updated and registered yearly.

Constituting Act “Estatutos Sociales”. Legal document where an Enterprise, Cooperative or Integradora is officially constituted into a commercial society with series of conditions such as having a function, a governing body, a legal administration, a set of decision making rules. It must contain the social objectives clearly expressed, as well as a list of its associates, along with the benefits which these are entitled to, and the sanctions that apply increase of failing to operate as agreed upon.

Cooperative Societies: (Sociedades Cooperativas de Producción Pesquera S C de RL)

Federal fisheries management structure and legislation enables and authorizes fishers cooperatives as well as private companies, industry and so called “free fishers” (Pescadores libres) to have concessions, permits and licences for fishing. However fisher cooperatives are the main producers for lobster fisheries and these have their own regulations and processes with internal rules that are governed by assemblies.

They are normally coordinated in a centralized manner by the state representatives of the Federation of Cooperatives, which in turn has a national representative, however each cooperative is independent and governs itself under the assembly structure which consists of a 1) President, 2) Secretary 3) Treasurer 4) Vigilance representative 5) four other substitute members “Vocales”.

Assemblies are the maximum decision organ for fishers, and where the definitions really take place regarding how many people can fish and under what conditions fishers must fish in specific areas. In general, cooperatives have fishing rights or concessions that are granted by the government for up to 20 years. Using these rights, the cooperatives are able to impose strict management over the areas where they hold the exclusive right to fish. In addition, the cooperatives also play a role in enforcement by having the vigilance committees which is normally and organ created and subsidised by government with funds awarded to the cooperatives. Using this each cooperative provides enforcement over its fishing area, including regulating fishing practices of its members, the number of members allowed to fish, watching and reporting any illegal fishing in their fishing areas. Cooperative assemblies assign their representatives for meeting with all committees and authorities involved at all levels, Municipal, State, Regional and Federal.

In general throughout this thesis document the cooperatives mentioned will be referred to as one of the entities indicated in the following table unless specified separately:

Table 12-1 The six fishing cooperatives working within the Sian Ka'an and Banco Chinchorro Biosphere Reserves which hold exclusive concession rights to fishing. They are the clients certified by MSC and are associates of Integradora de Pescadores de Quintana Roo. SA de CV.

| Cooperatives working in Sian Ka'an: | Cooperatives working in Banco Chinchorro: |
|---|--|
| <ul style="list-style-type: none"> • Pescadores de Vigía Chico S.C. de R.L. • Cozumel S.C. de R.L. • José María Azcorra S.C. de R.L. | <ul style="list-style-type: none"> • Langosteros del Caribe S.C. de R.L. • Pescadores de Banco Chinchorro S.C. de R.L. • Andrés Quintana Roo. S.C de R.L. |

Environmental laws: The Secretariat for Environment (SEMARNAT, PROFEPA, and CONANAP) also has faculties for enforcement and management over all fished resources if these are extracted within a Marine Protected Area, National Park, or Biosphere Reserve. Legislation linked to these bodies are also the Law of National Properties (1982, 1994), Law of National Waters (1992), General Law of Ecology and Environmental Protection (1988,1996) LEGEPA as well as Article 27 of the National Constitution.

National Legal Framework for ecolabels: Will be referred to as the current legal framework which is applicable to labelling *eco-labelling instruments and initiatives like the Chakay Lobster Brand within the national jurisdiction, with respect to the management of the *P. argus* (*Panulirus argus*), including but not limited to the following: Law for industrial Property (Ley de la Propiedad Industrial), Law For Commercial Entities (Ley General de Sociedades Mercantiles), Presidential Decree which promoted the creation of “Integrating Societies” (Decreto Presidencial que promueve la organización de Sociedades Integradoras), General Law for Cooperative Societies (Ley General de Sociedades Cooperativas), General Law for Sustainable Fisheries and Aquaculture (Ley General de Pesca y Acuacultura Sustentables y su Reglamento), National Fish Memo (Carta Nacional Pesquera), General Law for the Ecological Equilibrium and Environmental Protection, and its rules regarding Natural Protected Areas (Ley General del Equilibrio Ecológico y Protección al Ambiente y su Reglamento en materia de Áreas Naturales protegidas), Management Plans (Planes de Manejo), Federal Rights Law (Ley Federal de Derechos), No Take Season amendments (Avisos de Veda) and Official Mexican Norms (Normas Oficiales Mexicanas “NOM’s”).

Official Mexican Norms: “Normas Oficiales Mexicanas” (NOM’s) are legal instruments for particular purposes of technical character that regulate activities related to extraction, catch harvest and commercialization of lobster. NOM-006-PESC-1993 regulates harvesting of all lobster species in waters within the jurisdiction of the Gulf of Mexico and Caribbean, as well as the Pacific Ocean. NOM’s are Mexican Official Standards which deal with aspects such as regulating lobster minimum size of capture, limits mesh sizes, types of fishing gear used, and spatial restrictions. In addition to these it obliges those who do not have a permit or concession to participate in every program that is established for an efficient management of the fishery. The process of modifying NOMs involves the participation of stakeholders, NGOs and other interest groups in committees. The conducting of these committees is regulated by the Federal Metrology and Normalization Law (Ley Federal de Metrología y Normalización). CONAPESCA the fisheries regulatory agency is the one that governs and takes full responsibility these processes are promoted by stakeholder participation in the so called Fisheries Committees (Comites de Pesca) that must meet regularly by law. This is how several NOMs were developed between 1993 to 2000, which included traditional regulations such as permits, gear specifications, season closures, area closures, size limits, quota limits, and by-catch excluding devices.

For the purpose of this study NOM-128-SCFI-2006, is of relevant importance since it is related to labelling of products and certification of origin.

Management Programs in MPA’s: Instruments for jurisdiction within Natural Protected Areas which determine how conservation and harvesting of Natural Resources (including lobster) should be carried out, as is the case with the Biosphere Reserves of Banco Chinchorro and Sian Ka’an.

Permits: Will be referred to as the permits which are delivered by the corresponding authorities and agencies in favour of one or several Cooperatives which will guarantee their fishing activity by applying a series of predetermined conditions and rules for lobster harvesting agreed upon in an official assembly certified by a notary.

Sian Ka’an (SK): It will refer to as the whole Biosphere Reserve and a unit, although it officially refers to both of the Natural Protected Areas “Reserva de la Biosfera Sian Ka’an” and “Arrecifes de Sian Ka’an”, which were created through the presidential decree on the 20th of January 1986 and the 2nd of February 1998 respectively, found within the State of

Quintana Roo, with a surface area and characteristics as described in those decree and further described under the theme areas of study in this thesis.

13 List of publications Kim Ley as (*Ley-Cooper Kim*)

Published as first author:

1. **Ley-Cooper, K.**, de Lestang, S., Phillips, B. & Lozano-Álvarez, E. (2014) An unfished area enhances a spiny lobster (*Panulirus argus*) fishery: Implications for management and conservation within a Biosphere Reserve in the Mexican Caribbean. *Fisheries Management and Ecology*, 21, 264–274. (A)
2. **Ley-Cooper, K.**, de Lestang, S., Lozano-Álvarez, E. & Phillips, B. (2013) Estimates of exploitation rates of the spiny lobster fishery for *Panulirus argus* from tagging within the Bahía Espíritu Santo “Sian Ka’an” Biosphere Reserve, Mexican Caribbean *Marine Biology Research*, 9, 88-96.
3. **Ley-Cooper, K.**, Lozano-Álvarez, E., Phillips, BF., Briones-Fourzán, P. (2011) Proc. *Gulf Carib. Fish. Inst* Use of Artificial Shelters (“Casitas”) as an Alternative Tool for Stock Evaluation and Management of *P. argus* in Banco Chinchorro (México).
4. **Ley-Cooper, K.** (2010) Developing Sustainability Principles and Criteria for Management and Eco-labelling in the Sian Ka’an and Banco Chinchorro Biosphere Reserves, Mexico. *Proceedings of the 63rd Gulf and Caribbean Fisheries Institute*. San Juan, Puerto Rico.
5. **Ley-Cooper, K.** & Chávez, A. (2009) Bio-economic Modelling Applied to a Spiny Lobster Fishery of the North-western Caribbean In: GCFI (ed.) *Proceedings of the 62nd Gulf and Caribbean Fisheries Institute*. 62 ed. Cumana, Venezuela. (A)

Published as co-author

6. Bellchambers, L., Phillips, B., Pérez-Ramírez, M., Lozano-Álvarez, E., **Ley-Cooper, K.** & Vega-Velazquez, A. (2014) Addressing environmental considerations for Marine Stewardship Council certification: A case study using lobsters. *Marine Policy*, 50, 249-260
7. Nathan K. Truelove^{1,2}, **Kim Ley-Cooper**³, Iris Segura⁴, Patricia Briones-Fourzán⁴, Enrique Lozano-Álvarez⁴, Bruce F. Phillips³, and Richard F. Preziosi¹, (2015). "Genetic analysis reveals population structure among discrete size classes of

P. argus (Panulirus argus) within marine protected areas in Mexico" *Journal of Fisheries Research*.

8. Nathan K. Truelove, Sarah Griffiths, **Kim Ley-Cooper**, James Azueta, Isaias Majil, Stephen J. Box, Donald C. Behringer, Mark J. Butler IV, Richard F. Preziosi (2014). Genetic evidence from the spiny lobster fishery supports international cooperation among Central American marine protected areas. *Conservation Genetics*.
9. Genetic Connectivity of *P. argus* (Panulirus argus) in Belize. Nathan K. Truelove, Emily Burdfield-Steel, Sarah Griffiths, **Kim Ley-Cooper**, Richard Preziosi, Mark J. Butler, Donald C. Behringer, Stephen Box, and Steven Canty. *Proceedings of the 64th Gulf and Caribbean Fisheries Institute*.

Reports:

10. **Ley-Cooper, K.** (2009) Implementación del programa de manejo sustentable, monitoreo y comercio justo de la Marca Colectiva de Langosta: "Chakay de las Reservas de la Biosfera de Banco Chinchorro y Sian Ka'an". Playa del Carmen, Quintana Roo: Colectividad RAZONATURA A.C.
11. **Ley-Cooper, K.** & García-Rivas, M.C. (2009) Experiencia de Captura de Langosta Viva en la Reserva de la Biosfera de Banco Chinchorro N0.32 PP.

In progress to be submitted to a peer reviewed journal:

12. **Kim Ley-Cooper**^{1*}, Simon de Lestang², Patricia Briones-Fourzán³, Enrique Lozano-Álvarez³, Bruce F. Phillips¹, Ravi Fotedar¹. *In review* Environmental effects derived from cold fronts increase catch rates of spiny lobsters in a Mexican Caribbean Biosphere Reserve fishery.