EFFICACY OF THE EASTPORT MARINE PROTECTED AREA FOR AMERICAN LOBSTER, *HOMARUS AMERICANUS*

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ABSTRACT

Given global targets of protecting 10% of marine habitats by 2020, managers increasingly looked to Marine Protected Areas (MPAs) as a conservation tool. The Eastport MPA, designated in 2005, was established to protect a portion of the local American lobster (*Homarus americanus)* population. To determine MPA impacts on local lobster growth and reproduction, I analyzed 15 years of capture-mark-recapture data and egg samples from Eastport. Despite no significant trend in fecundity or size along a distance gradient from the MPA boundary, I detected increased egg production over time in the MPA. Female growth inside and outside remained steady over the tagging period in contrast to more variable male growth. Comparison of Eastport population fecundity and growth to other populations indicated higher fecundity at commercial size and slower rate of growth. These analyses provide inconclusive evidence regarding attainment of the original MPA conservation objectives, however, community-driven conservation could provide ecological benefits such as more careful handling of lobster that indirectly support these broader Eastport MPA objectives.

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LIST OF ABBREVIATIONS AND SYMBOLS

AIC	Akaike Information Criterion
BACI	Before After Control Impact
C or CL	Carapace length
°C	Degrees Celsius
CMR	Capture Mark Recapture
CPUE	Catch Per Unit Effort
D	Distance
DFO	Department of Fisheries and Oceans
EPLMA	Eastport Peninsula Lobster Management Area
EPLPC	Eastport Peninsula Lobster Protection Committee
F	Fecundity
FRCC	Fisheries Resource Conservation Council
GPS	Global Positioning System
GLM	Generalized Linear Model
Km	Kilometers
km^2	Kilometers Squared
L	Carapace Length
logLik	Log Likihood
Lbs	Pounds
LFA	Lobster Fishing Area
M	Meters
Ml	Millilitres
mm	Millimeters
MPA	Marine Protected Area
N	Number

°N	North
R^2	R squared (coefficient of determination)
SE	Standard Error
um^2	Micrometre
U.S.	United States

CO-AUTHOURSHIP STATEMENT

The research described in this thesis was designed, and written by V. Howse, with input from committee members P. Snelgrove, D. Schneider, C. Konrad, and R. Stanley. All data analyses were conducted by V. Howse, with assistance from D. Schneider, C. Konrad and R. Stanley. Authorship of Chapters 2 and 3 will evolve as the manuscripts mature; however, V. Howse will be lead author and will include those who made significant contributions to manuscript development as co-authors.

CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

1.1.1 Marine Protected Areas

Increasing human populations globally place many marine systems under constant and sometimes increasing pressure. This pressure and associated disturbances threaten marine populations, habitat, and biodiversity, and its impacts underpin an increasing worldwide move towards spatial marine conservation measures (Halpern et al. 2008). Marine Protected Areas (MPAs), in particular, have become the fastest-growing ocean use management tool to address conservation, biodiversity loss, and marine management concerns globally (Lester et al. 2009; Claudet 2010; Pendred et al. 2016; Hameed et al. 2017). MPA is a term that generally refers to geographic areas (in the marine environment) that are given greater protection from removal, disruption or human interference than the surrounding waters with the intent to preserve natural and/or cultural resources, often by prohibiting or limiting fishing or other human activities (Wenzel and D'lorio, 2011; Ley-Cooper et al., 2014). For consistency, from this point on I use the term 'Marine Protected Area' when referring to marine closures, marine refuges, sanctuaries, parks, or for no-take zones or protected areas. Increasingly, managers apply MPAs as a tool to mitigate disturbances caused by fishing or marine traffic, to enhance protection for special marine areas (*i.e.* highly productive, diverse or unique), or as a preventative protective measure for vulnerable or pristine systems *(i.e.* deep ocean, sensitive corals or sponges) (Côte et al. 2001; Huserbråten et al. 2013). Fully protected areas that exclude extractive activities (*i.e.*, no-take MPAs) often produce positive species and ecosystem responses, including increases in biomass, density, and overall species diversity (Palumbi 2004; Mateos-Molina et al. 2014; Rossetto et al. 2015; Young et al. 2016).

When applied to protect a commercially exploited species, MPAs can allow an unexploited portion of the population to develop and survive to maturity, which in turn can potentially result in increased production and fisheries recruitment (Goñi et al. 2010). The magnitudes of these ecological responses rely on two factors: an MPA's design (location, size, specific restrictions) and its population connectivity to exploited population (the degree of movement of animals between the MPA and surrounding unprotected areas). Marine refuges that protect critical spawning stocks can increase recruitment and genetic diversity, and/or broaden population structure, which ultimately can promote a healthy ecosystem and, in turn, boost local fisheries (Bellier et al. 2013). For MPA objectives focused on achieving positive outcomes outside the MPA boundary, success often means increased productivity that results in adult spillover or larval subsidy to adjacent fishing areas that yield benefits to the surrounding fisheries (Palumbi 2004 and Daigle et al. 2016). The ability to detect spillover and gauge the success of a fisheries-focussed MPA often depends on how well the fishery was managed prior to MPA implementation; the benefits realized from increased recruitment typically occur in previously depleted populations or species (Buxton et al. 2014), assuming depensation (Myers et al. 1995) has not occurred.

Many challenges must be considered when developing, monitoring, and managing MPAs. Measuring the impact of an MPA unambiguously requires baseline data prior to establishment in order to attribute an ecological or demographic trend to the management intervention. For MPAs that prioritize larval export as a conservation outcome, linking any change in recruitment or demographic signal (scaled to assessment area) to the MPA may prove difficult. This challenge is particularly evident for species such as lobster, where potential larval transport distances greatly exceeds the boundaries of the reserve, obscuring any measurable benefits associated with increased productivity to the surrounding fishery, and highlighting the need to consider connectivity when designing closures (Roberts 1997). For MPAs that rely on adult spillover out of an MPA, the surrounding habitat may affect the distribution of the target species (Young et al. 2016). Challenges in the design and monitoring of an MPA vary greatly depending on the target species, conservation goals, and location of the MPA (Green et al. 2015; Lee et al. 2015).

1.1.2 The Newfoundland Lobster Fishery

In the cold northwestern Atlantic, residents of the province of Newfoundland and Labrador traditionally made their living harvesting Atlantic cod and other groundfish over the 500-year history of the fishery (Rose 2004). In the early 1990s, however, landings of groundfish rapidly declined and subsequently collapsed (FRCC 1995). By 1993, widespread moratoria on groundfish were implemented throughout the Canadian northwest Atlantic, resulting in the largest layoff of workers in Canadian history. The effects of the economic downturn were particularly pronounced in Newfoundland and Labrador and persist today. The loss of the groundfish fishery amplified a focus on management and productivity, and Newfoundlanders and Labradorians began to take pride in sustainably managing remaining fisheries, such as the economically important American lobster (*Homarus americanus*).

Though not as significant as the groundfish fishery historically, provincial documents record lobster fishery statistics starting around 1874. These records list the earliest annual landings at 150,000 lbs. increasing up to 17.5 million lbs. by 1889 (Ennis 1982). For years lobster remained a secondary fishery for many participants, contributing to the loose regulations associated with the fishery, and landings that plummeted to 750, 000 lbs by 1924 (Ennis 1982). With fluctuating landings and the vast majority of yield shipped live to United States markets in the 1950s, the fishery remained highly unstable. At that time, management strategies were limited to setting *minimum legal sizes* and *protection of egg bearing (berried) females,* driven by strict requirements from the U.S. on imports. In 1976 the implementation of limited entry licenses for the first-time restricted trap numbers per holder (Ennis 1982). Since 1990 the number of lobster licenses has decreased by 47%, with approximately 2400 licenses issued throughout the province (DFO 2019a). Lobster currently represents the most valuable commercial fishery in Atlantic Canada. In 2017 the Atlantic Canadian lobster fishery generated 1.46 billion dollars (with over $44.6 million from Newfoundland), far exceeding the combined value of $227 million for all groundfish fisheries in Atlantic Canada ($118 million in Newfoundland) (DFO 2019b).

Lobster fishery management varies among the Atlantic provinces and, within each designated management unit, or Lobster Fishing Area (LFA). Many of these conservation management measures aim to maintain or boost egg production (FRCC 1995). One conservation strategy involves v-notching, a common voluntary measure where fishers cut a small notch in female tails. The presence of the notch ensures immediate release of the individual until the notch grows out, so the female can continue reproducing. To increase average brood sizes, managers implement slot fisheries that limit fishing between a minimum and maximum carapace sizes (Seiden et al. 2013). Thus, v-notching, slot fishing, and marine protected areas are common strategies to promote sustainable lobster fisheries (Xu and Schneider 2012). Other harvest control rules such as seasonal closures further promote the longevity of commercial fisheries, including lobster and many other species.

1.1.3 The Eastport Marine Protected Area

In 1995, after recommendations from the Fisheries Resource Conservation Council (FRCC) encouraging the implementation of egg production efforts, lobster harvesters from the Eastport Peninsula area (from eight communities; Eastport, Salvage, Burnside, Sandringham, St. Chad's, Sandy Cove, Happy Adventure and St. Brendan's) self-organized the Eastport Peninsula Lobster Protection Committee (EPLPC) (FRCC 1995; DFO 2013). The group identified two areas, Duck and Round Islands, as voluntary fisheries closures (Figure 1) to act as a refuge for local American lobster (*Homarus americanus)* (Janes 2009). In 2005, these areas, collectively covering an area of only 2.1 km^2, received official designation as an Oceans Act MPA, restricting extractive human activity inside the outlined boundaries, including the seabed and subsoil to depths of two meters (Department of Justice 2005). Though consistent with many small tropical marine protected areas designed to protect discrete coral reef systems, the small size of the Eastport MPA raises questions regarding the efficacy of such a small area for enhancing a species such as lobster that disperses widely – both at a larval and adult stages. Additional conservation measures implemented in the LFA where the Eastport Marine Protected Area is located, include protecting v-notched and berried females from landings. However, Department of Fisheries and Oceans (DFO) management enforces a minimum legal size of 82.5mm with no maximum legal size (Xu and Schneider 2012).

Criticized for its small size, the Eastport Peninsula Lobster Management Area (EPLMA) covers 400 km^2, with only 2.1 km^2 designated as an official MPA (Department of Justice 2005; Janes 2013). The area within the MPA itself is fully closed, restricting all commercial and recreational fishing activity. This is complemented by other conservation measures in the remainder of the EPLMA that include a fishing season that prohibits harvesting during peak lobster molting and mating periods, exclusive fishing access for harvesters from the Eastport Peninsula communities, and a 150 trap limit (per licence). Other conservation measures in the EPLMA include voluntary v-notching and a tag recapture monitoring program.

Globally, many marine reserves are relatively small in size, and the Eastport MPA falls in the 55th percentile, not far from the global average (Stanley et al. 2015). For a protected area about 1 km^2 in size, a vagile species with high dispersal potential may nonetheless benefit from the conservation area (Palumbi 2004). However, in the case of the Eastport Marine Protected Area, the 2.1 km^2 covers less than 1% of the Lobster Fishing Area (LFA) and less than 0.1% of the Eastport Peninsula Lobster Management Area (EPLMA). Duck and Round Islands were initially identified as suitable lobster habitat and subsequently chosen for fisheries closures, based on local knowledge. However, before implementation of the MPA no habitat survey was conducted inside or outside the MPA. A subsequent Eastport mapping study (Novaczek et al. 2017) described the habitat within the MPA habitat as substrates dominated by algae, with rocky shallows at the coast moving to sand in deeper areas of the MPA. The mixed rocky habitat is conducive to juvenile lobster substrate requirements, and the area provides complex characteristics and crevices utilized by the American lobster (Novaczek et al. 2017).

Monitoring of the Eastport MPA involves an annual mark-recapture program that first started in 1997, conducted in the fall inside and outside the MPA throughout the EPLMA. Harvesters execute the tagging program outside of the fishery and missed only one year (2003) of data collection since monitoring began. Harvesters also collect at-sea-sampling and logbook data during the lobster fishery throughout LFA 5 where the MPA is situated (DFO 2013). The tagging program provides information on comparative size and the population structure of lobster inside and outside the MPA (DFO 2013). Previous studies monitoring the effectiveness and impact of the MPA examined exploitable biomass, lobster abundance, movement, catch per unit effort (CPUE), estimate of berried females, reproductive potential relationships, length frequency distribution, average carapace lengths (CL), sex ratio, and rates of v-notching (Janes 2009; Lewis et al. 2017).

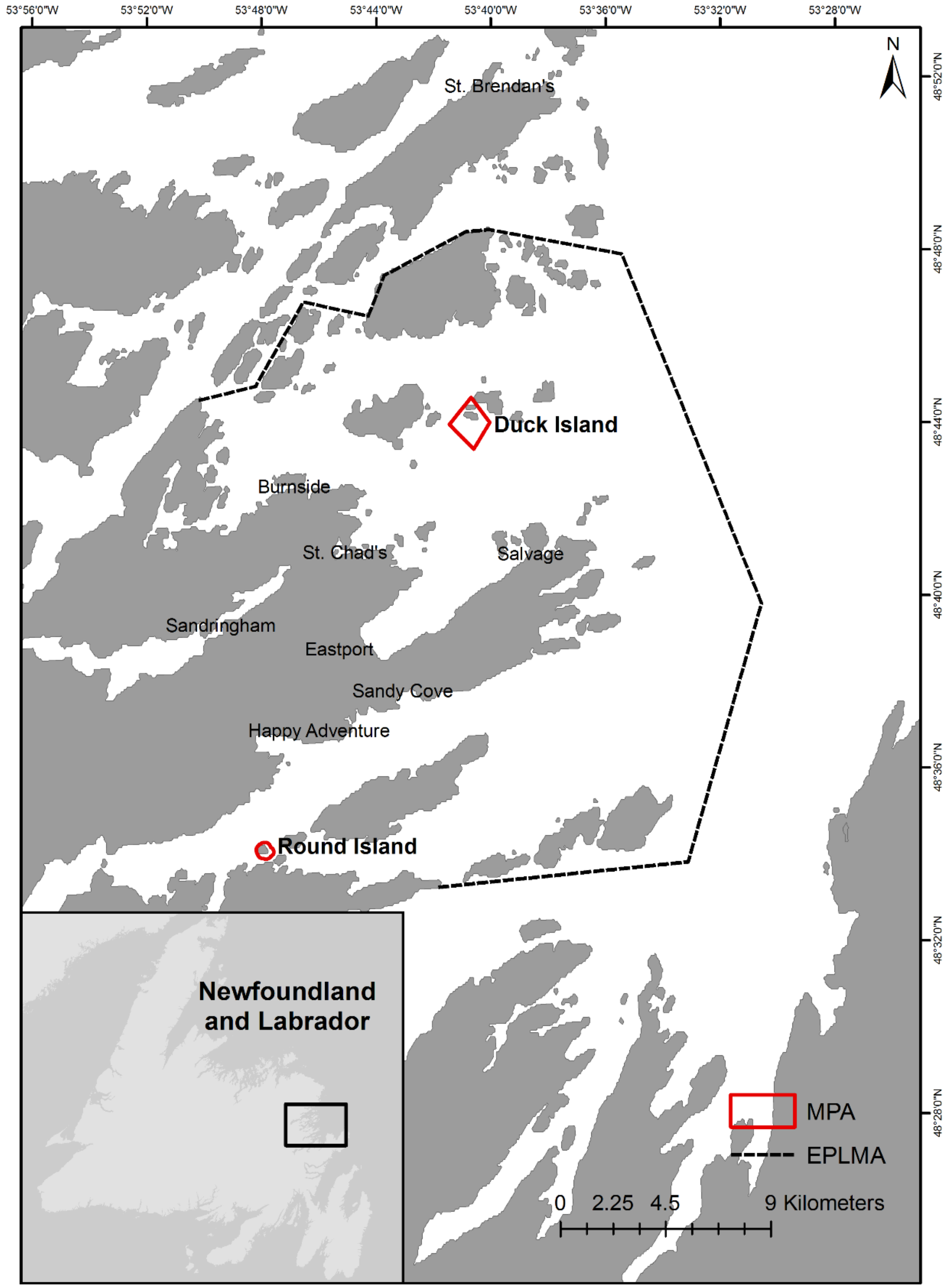

Figure 1: The Eastport Marine Protected Area (MPA) Duck and Round Islands (collectively covering 2.1 km^2), located in the 400 km^2 Eastport Peninsula Lobster Management Area (EPLMA), Bonavista Bay, Newfoundland and Labrador.

1.1.4 Lobster Biology and Geography

American lobster is a long-lived species with indeterminate growth that molts through a stepwise growth-pattern (Chang et al. 2012; Xu and Schneider 2012). Their growth includes two phases: the first phase that involves molting within a set time frame, and the second phase that occurs as lobster increase in length (Fogarty 1995). Female lobster typically spawn during the spring or summer, with water temperature (between 10 °C and 13.8 °C in Newfoundland; Ennis 1995) influencing the onset of spawning. Females can produce up to 10,000 eggs at a time and their fecundity increases with body size (Talbot and Helluy 1995). As benthic, crevice-dwelling adults, reproductively active females release larvae into the water column, which, after completing three pelagic larval stages settle to the bottom as post-larval stage IVs (Factor 1995). The size of maturity for American lobster differs greatly across their geographic range and developmental maturity occurs at smaller sizes for males than females; functional maturity occurs for males when they are physically capable of reproducing and given opportunity to mate (Lawton and Lavalli 1995).

Temperature limits the distribution of American lobster, which historically ranged from North Carolina to Newfoundland (Lawton and Lavalli 1995) at depths from the low tide line to 600 m (McMahan et al. 2016). They tolerate temperatures spanning from the subarctic waters of Newfoundland (which drop to -1.5°C (Han et al. 2015)) to the temperate waters of North Carolina (max 24 °C) (Lawton and Lavalli 1995). However, this range is shifting north in response to ocean warming (Wahle et al. 2009a; Wahle et al. 2015; Oppenheim et al. 2019) to a new range that extends from New Jersey (Kenchington et al. 2009) to the Strait of Belle Isle off coastal Labrador (DFO 2016). Within their range, they occupy a variety of habitats from bedrock to sandy substrates (Lawton and Lavalli 1995), and from coastal and offshore areas in the Gulf of Maine to the outer edge of the Scotian Shelf (Cook et al. 2017). Movement varies within the benthic life stages, from short movements of 10s of km to long-term movements over 100 kms for offshore lobster (Cooper and Uzmann 1971; Campbell and Stasko 1985; den Hayer et al. 2009). Lobster in Newfoundland, and specifically Bonavista Bay, tend to follow more localized and short-distance seasonal movements near shore (Ennis et al. 1989; Ennis 2011). Larval transport varies greatly, generally exceeding distances of adult movement, and depending on wind, currents, and directional swimming (Katz et al. 1994; Chasse and Miller 2010).

1.1.5 Goals and Objectives

Marine conservation science often seeks to measure effectiveness of intervention efforts and to quantify the impact of these efforts on local populations, fisheries, and their ability to achieve the specific conservation goals associated with that management intervention. Despite expected reduction in fishing pressure by establishing a refuge, and, in turn, potentially increasing growth and reproduction, many assessments lack evidence to demonstrate that MPAs have achieved their conservation objectives (Jameson et al. 2002; Mora et al. 2006; Garces et al. 2013). Researchers often measure MPA effectiveness through biological indicators such as increased biomass, species richness, density, reproductive potential, growth rates, and spillover of individuals into the surrounding habitat (Lester et al. 2009; Bevacqua et al. 2010). Protected areas that focus primarily on fisheries enhancement require export of a sufficient number of individuals to compensate for the amount of fishing ground lost to the protected region and to achieve their conservation objective (Jameson et al. 2002).

Managers often use changes in egg production, mortality, growth rate, and catch per unit effort over time to determine fisheries stock health (Miller 2003). To date, assessments of the

Eastport Marine Protected Area and its lobster stock have used four indicators of stock status: estimates of population abundance from tagging studies, CPUE from at-sea sampling data, estimates of berried females, and population size structure or length-frequency distributions (Lewis et al. 2017). These metrics indicate a small but statistically insignificant increase in the Eastport MPA population abundance over time, with no significant trends in CPUE. Analysis of lobster in the broader Lobster Fishing Area (LFA) 5 indicates increased egg production based on an increase in average carapace length over time (Lewis et al. 2017), however, deciphering whether to attribute this effect to the MPA or other conservation efforts such as v-notching remains challenging. Despite documented general increases in average carapace length within the EPLMA these data cannot disentangle the underlying dynamics, notably individual growth and fecundity (Lewis et al. 2017). These variables have yet to be estimated for this population in relation to MPA protection.

This dissertation has two primary objectives. First, I quantify local fecundity estimates and how the MPA might potentially contribute to egg production in the local lobster population of the broader EPLMA. Second, I explore a 20-year mark-recapture data set collected inside and outside the Eastport MPA to model individual growth rates over time. From this modeling work, I compare growth rates inside and outside the MPA to growth curves for lobster populations throughout their range. Both chapters discuss the use of indicators of performance of the Eastport MPA since its implementation.

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CHAPTER 2: QUANTIFYING FECUNDITY AND REPRODUCTIVE OUTPUT OF EASTPORT MARINE PROTECTED AREA LOBSTER

ABSTRACT

Following establishment of the fishing grounds near Eastport, Newfoundland and Labrador in 1997 as a fisheries closure to enhance the local lobster population, Fisheries and Oceans Canada designated the region as a Marine Protected Area (MPA) in 2005. This study compares methods of estimating fecundity and addresses the importance of obtaining local fecundity estimates. In comparing two methods of measuring fecundity, the standard fecundity at length equation ($F = aL^b$) and the general latitude model of fecundity, I found no significant difference between these methods and substantial overlap in the 95% confidence intervals. The Eastport lobster population has higher fecundity at lower carapace lengths than other populations in Canadian and American waters throughout the range of the species. In order to quantify the contribution of the MPA to regional reproductive output I simulated egg production from density, sex ratio, and local measures of fecundity, and found the egg production from the MPA to be $0.74\% \cdot \text{year}^{-1} \pm 0.22\%$ of the entire Eastport Peninsula Lobster Management Area. The MPA therefore contributes modestly to regional egg production, with unknown contributions to local population persistence.

2.1 INTRODUCTION

Marine Protected Areas (MPAs) are increasingly used as a management tool globally to protect biodiversity, promote ecosystem resilience, and facilitate the sustainable use of marine resources (Fox et al. 2014; Gill et al. 2017). In many cases, MPAs are designed to complement and enhance conventional fisheries management, by offering long-term and comprehensive protection to biota and habitat that can increase productivity and spillover to surrounding fishing areas (Chollett et al. 2016). Ideally such refuges reduce overall mortality (*i.e.,* by limiting or excluding fishing) which, in turn, contributes to an increase in individual size and the probability of an individual entering the reproductive segment of the population, which subsequently results in higher productivity and spillover to adjacent fishing areas. Given the challenge in measuring increases in larval settlement and recruitment into the population, researchers often use spillover as a proxy of MPA benefits through increased density and reproductive output (Goni et al. 2010). Providing refuge to reproductively active individuals from a fishery can also enhance spawning stocks within a population (Maxwell et al. 2013) which, in turn, can increase larval export that could potentially enrich surrounding fisheries (Côté et al. 2001). Many researchers consider fisheries closures and MPAs important tools for maintaining and increasing egg production and supplying neighbouring fisheries with offspring (Roberts et al. 2001), while acknowledging the difficulty of quantifying these benefits (*e.g.,* Ennis 2011), even if they occur (Buxton et al. 2014). Many factors contribute to the success or failure of spatial closures, but the strongest positive responses generally occur in reserves targeting low mobility or fully sedentary species that otherwise experience high fishing mortality (Hilborn et al. 2006; Barnes and Sidhu 2013; Moland et al. 2013).

Objectively evaluating, quantifying, and monitoring the benefits of a protected area presents a significant challenge to managers. Often MPAs are set up with diverse conservation objectives that manifest responses at multiple spatio-temporal scales. Indeed, species identified as conservation priorities may vary temporally in abundance, interconnecting with the surrounding seascape at a variety of spatial scales through larval dispersal and adult movement (Ojeda-Martinez et al 2007; Burgess et al. 2014; and Green et al. 2015). The level of compliance to the management goals of the MPA can impair understanding of the value of MPAs. Effective understanding of an MPA's roles in influencing biological productivity to the presumed protection level requires effective monitoring and enforcement of the MPA regulations (Lester et al. 2009 and Mateos-Molina et al. 2014). In these cases, managers should consider how activity within surrounding unprotected locations influence those processes within the MPA. Any benefits accrued by the MPA may be offset by increased fishing activity in adjacent fishing grounds just outside the protected area boundaries (Chollett et al. 2016).

Multiple no-take reserves for lobsters around the globe demonstrate the potential to protect and sustain lobster populations. In many cases protected populations have increased appreciably and at-times rapidly as a result of refuge from fishing. For example, the Leigh Marine Reserve (a 5.18 km^2 reserve that extends 800 m from shore) in New Zealand was closed to all fishing activity in 1975 (Walls 1998), with ongoing commercial fishing for rock lobster *(Jasus edwardsii)* around the reserve boundary since 1980. Lobster have increased in mean size and abundance within the reserve since its establishment, and commercial catch rates around the boundary have been high compared to areas away from the reserve, despite increased fishing pressure near the boundary (Kelly et al. 2000; 2002). Numbers of large (> 82.5 mm) spiny lobster (*Panulirus interruptus)* at a network of protected areas in Santa Cruz and Santa Rosa Islands, California, were greater inside than outside the reserves. Benefits were evident within 5-6 years of the establishment of the reserve and included larger mean sizes, larger class size, and greater trap yields surrounding the closure (Kay et al. 2012).

Despite its small size (~0.29 km^2), the Merri Marine Sanctuary in Southwest Victoria, Australia established in 2002 supports a large population of rock lobster (*J. edwardsii*) (Young et al. 2016) with increasing size and abundance of lobster inside the sanctuary since establishment. Size and abundance of lobster outside the MPA also increased close to the boundary, suggesting that the reserve augments the surrounding population and fishery (Young et al. 2016). On Norway's Skagerrak coast, three small MPAs, the Kvernskjær (0.5 km^2), Flødevigen (1 km^2) and Bolærne (0.7 km^2) lobster reserves, have been closed to the commercial European lobster (*Homarus gammarus)* fishery since 2006, allowing a Before-After-Control-Impact (BACI) approach to quantify MPA impacts (Moland et al. 2013). For all three MPAs, lobster increased significantly in abundance and size after the MPA implementation, inside relative to outside (Moland et al. 2013). Measuring spillover can be challenging, particularly for species with meroplanktonic life stages such as American lobster (*Homarus americanus*), because spatial scales of connectivity for pelagic larvae can be substantially greater than in the later benthic life history phases (Stanley et al. 2015). In a tagging study, Morse et al. (2018) found that adult lobster moved a mean distance varying between 1.1 to 25 km in one year, whereas their modelled larval movement traversed mean distances of 71 km downstream and 2 km upstream. In cases where the signal from larval production extends well beyond the boundaries of the management and/or reserve area, measuring success of spillover must rely heavily on documenting adults moving out of or increasing in numbers within the protected area (Gell and Roberts 2003).

Declining catches in Newfoundland during the mid-1990's spurred concerns about possible widespread recruitment overfishing, a situation where fishing reduces stock levels so low that recruitment is impaired (Sissenwine and Shepherd 1987). A major review of lobster conservation in the Atlantic provinces by the Fisheries Resource Conservation Council (FRCC) determined that high exploitation levels and low egg production posed a high risk of recruitment overfishing. The FRCC recommended that management should focus on maintaining egg production through reduced effort (*e.g.*, more v-notching or increased minimum legal sizes) and/or marine reserves (FRCC 1995; Ennis 2011). Since the 1995 report, the Newfoundland Region of Fisheries and Oceans Canada has implemented conservation efforts including 10 lobster closures around the island that prohibit the use of scallop dredges or lobster fishing in areas of known lobster habitat to help protect lobster and promote egg production (DFO 2010). In the Eastport Peninsula Lobster Management Area in 2008, the Department of Fisheries and Oceans (DFO) reduced the trap limit per license from 200 to 150 (Lewis et al. 2017). Other efforts around the province have included voluntary v-notching to allow females to reproduce before the fishery removes them (Xu and Schneider 2012), and slot fisheries that involve enforcing a minimum and maximum size limit with the goal of protecting larger lobster, which produce exponentially more eggs than smaller lobster (Aiken and Waddy 1980; Xu and Schneider 2012; Seiden et al. 2013).

In 1997, local harvesters of the Eastport Peninsula established the EPLMA in response to the FRCC report promoting egg conservation measures (FRCC 1995). The EPLMA encompasses a 400 km^2 region that includes two closed areas, Duck Island and Round Island, which comprise the 2.1 km^2 MPA (Figure 1). The two closed areas received official MPA designation under the Oceans Act in 2005 (DFO 2014), though unofficial cessation of fishing activity began in 1997. The conservation objectives of the Eastport MPA focussed on maintaining a viable population of American lobster within the EPLMA, while engaging stakeholders and the public to participate in resource management and conservation awareness. The Eastport MPA monitoring program primarily involves scientific, enforcement, and compliance monitoring, and public education initiatives (DFO 2013).

Homarus americanus is a benthic decapod crustacean that historically ranged from Cape Hatteras, North Carolina to the Strait of Belle Isle, Newfoundland and Labrador (Lawton and Lavalli 1995), however, commercial catches south of Rhode Island are now negligible (Thunberg 2007). They hatch as meroplanktonic pelagic larvae that subsequently settle to the benthos as post-larvae. Using data on wind, currents, and directed swimming (Stanley et al. 2016), models estimate larval dispersal distances of 10s to 100s of km (Katz et al. 1994; Incze et al. 2010) with predicted distances up to 805 km (Quinn et al. 2017). Fecundity of American lobster increases exponentially with body size; egg numbers range from a few thousand for smaller individuals to tens of thousands in larger, older lobster (Aiken and Waddy 1980; Talbot and Helluy 1995; Currie et al. 2011). Size at maturity of American lobster varies with location and can change with time, from as low as 60 mm (Haarr et al. 2017) to as large as 108 mm carapace length in Atlantic Canada (Campbell and Robinson 1983). Multiple studies link spawning timing to water temperature (Aiken and Waddy 1986; Talbot and Helluy 1995), with spawning generally beginning in early summer when temperatures exceed 12 °C (Harding et al. 1982). Temperature and body size also influence individual reproductive activity (Aiken and Waddy 1980; Ouellet and Plante 2004; Waddy and Aiken 2005). Large lobster (120-150 mm carapace length) can spawn (release eggs) twice in the time period between molts whereas smaller individuals (<120 mm) may only spawn 1-2 months after molting (Waddy and Aiken 2005). The presumably small contribution associated with 2.1 km^2 of potentially increased productivity from protected area relative to natural variability and total productivity of the broader system complicates any effort to demonstrate measurable success of the Eastport MPA in achieving this primary objective. Nonetheless, stakeholders frequently seek evidence demonstrating benefits associated with reduced access to sustain their support for management interventions such as MPAs (Claudet 2011).

Previous research on the Eastport MPA focused on estimating lobster population structure inside and outside the MPA, density, reproductive potential, and monitoring changes in mean carapace size, berried female proportions, and movement of lobster through the EPLMA (Janes 2009; Collins 2010; DFO 2014). Janes (2009) reported a higher percentage of large, berried females and a higher proportion of berried females in the Eastport MPA than outside in the fished area. Collins (2010) reported the mean size of female and male lobster increased over time in the MPA but noted no increase in lobster densities. Larger individual lobster provide greater individual reproductive output because of their higher fecundity, with larger high-energy content eggs, larger larvae (Stanley et al. 2016), and more frequent spawning when compared to smaller individuals (Aiken and Waddy 1980; Attard and Hudon 1987; Ouellet and Plante 2004; Currie and Schneider 2011). Density of lobster calculated from estimated abundance within an area suggest a higher population density inside the MPA than outside (Lewis et al. 2017). Increases in lobster density in an MPA suggest increased reproductive output. However, size of maturity can change with increasing population density, thereby impacting reproductive output (Gardner et al. 2006). Despite reported increases in abundance, size, and number of berried females inside the Eastport MPA (Janes 2009; Collins 2010; DFO 2014), no study has quantified the contribution of the MPA to the greater EPLMA population. For species with low to moderate adult mobility, multiple studies demonstrate higher yields of CPUE near MPAs, extending from a few hundred to thousands of meters away (Goni et al. 2008). For example, in Columbretes Islands Marine Reserve in the Mediterranean Sea, analysis of tag-recapture, fishing surveys, and commercial data, detected a gradient of decreasing spiny lobster (*Palinurus elephas*) density up to 4.5 km from the reserve (Goni et al. 2006).

My study addresses the importance of establishing local measures of fecundity, and how they vary throughout the species range. Lobster fisheries and their respective management measures vary dramatically among regions in terms of landings and fishing mortality to minimum legal size and season dates. Fisheries and conservation management measures often depend on local measures of growth, fecundity, size of maturity, and recruit size to inform these decisions (Campbell and Robinson 1983; Pringle et al. 1983; Fogarty and Gendron 2004). I measured local fecundity of female lobster throughout the EPLMA and based on previous accounts of larger and higher proportion of berried females inside the MPA, I examine the distribution of these more fecund females near the MPA boundaries. I compare the Eastport fecundity results to fecundity measures throughout the species range to highlight differences among populations and provide a local estimate to assist with future management measures for the EPLMA. No fishing is permitted in the MPA, therefore I was unable to obtain samples inside the MPA boundary. However, from available observations and sampling opportunities, I was able test whether a greater number of large, berried females occur near the boundaries of the MPA than in the surrounding unprotected areas. Pairing results from a previous study (Lewis et al. 2017) with data collected for this project I estimate surplus egg production, defined as the difference between the estimated egg production of females near the MPA boundary compared to egg production from an area outside the MPA of an equivalent size. Evidence of larger females and a higher proportion of berried females inside the Eastport MPA (Collins 2010) motivated this test for a size gradient of fecundity as a function of proximity to the boundary of this MPA. A gradient of high density and CPUE close to an MPA boundary characterizes reserves that protect species with limited mobility (Goni et al. 2006). I compare methods of estimating fecundity and how estimates can differ regionally, to highlight the importance of obtaining localized information of lobster fecundity. I aim to understand how fecundity and increased egg production relate to MPA management and determine how the MPA contributes to the initial conservation goals of maintaining a viable lobster population.

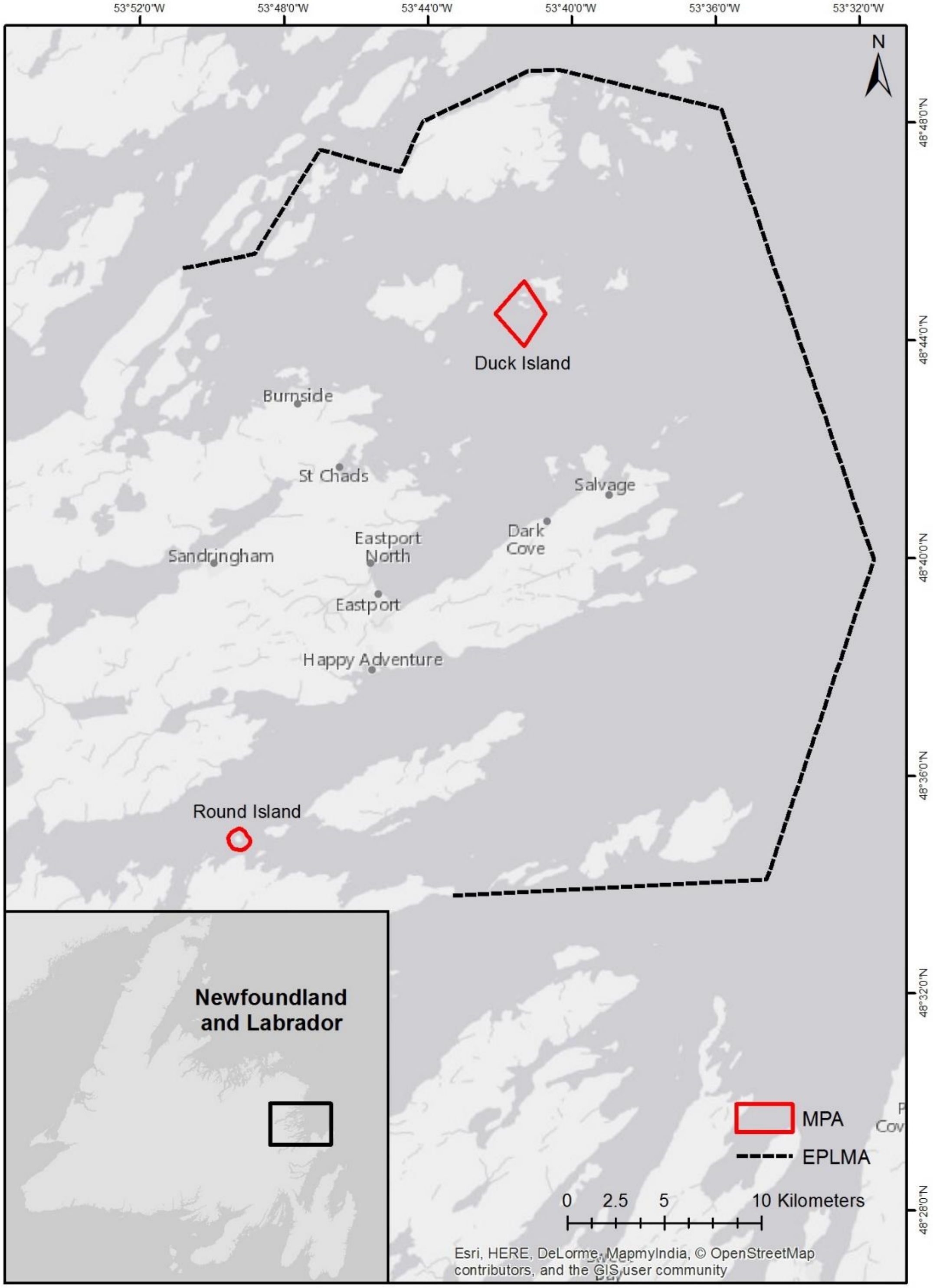

Figure 1: The Eastport Marine Protected Area (MPA) Duck and Round Islands (collectively covering 2.1 km^2), located in the 400 km^2 Eastport Peninsula Lobster Management Area (EPLMA), Bonavista Bay, Newfoundland and Labrador.

2.2 METHODS

2.2.1 Study Site

Fieldwork was conducted in waters adjacent to the Eastport MPA, which surrounds Duck and Round Islands (Figure 1), collectively covering 2.1 km^2 (Janes 2013). Stakeholders identified consistent presence of berried female lobster in waters surrounding these islands, representing prime spawning and brooding habitats for lobster in the area (DFO 2007)

2.2.2 Berried Female Sampling

During June 2013 and May-June 2014, I collected samples from locations surrounding Salvage, Eastport, and Happy Adventure (Figure 1). Sampling occurred during the fishing season on commercial vessels using standard traps. This collaboration allowed for the collection of egg samples to estimate fecundity, from fully formed egg masses prior to their releasing larvae, which typically occurs early in the summer months, when larvae benefit from rising temperatures that increase growth and survival (Ennis 2011). The fishery captures a limited range of female sizes, in that small lobster can escape from traps and those over 150 mm typically cannot fit in traps, resulting in carapace lengths from 68 to 151 mm. All traps were baited and left overnight before retrieval the following morning. Sample sites spanned the EPLMA surrounding both Duck and Round Island (Figure 1). I recorded capture locations (Figure 2)(GPS) and carapace length of each berried adult female sampled.

2.2.3 Egg Collection and Measurements

I estimated individual fecundity for each sampled lobster using an indirect, minimally invasive method developed by Currie et al. (2010). For each berried female captured, I used Mitutoyo 530-104 calipers and a depth gauge to estimate the volume of the egg mass by measuring the length of the entire egg mass and the height of each segment of the egg mass. I gently excised 10 eggs to obtain a relatively non-invasive fecundity measure using a micro-scoopula and stored them in a 20 ml scintillation vial of 5% buffered formalin-seawater solution.

To measure individual egg size, I placed eggs in a petri dish under a Leica M125 dissecting scope, teasing apart any eggs with connective tissue and removing any residual tissue. A Leica DFC490 camera and Leica Application Suite software captured images of the eggs, which I imported into ImageJ for analysis of egg surface area (μm^2) using a custom Java® based ImageJ macro. The program measures egg perimeter, circumferences, roundness, and also calculates egg diameter. I then estimated egg number per female based on the average egg volume from each sample, estimated egg mass volume, and a compaction factor of 0.535 to account for the packing density of eggs on a given female (Currie et al. 2010).

2.2.4 Estimating Sample Distance

I used the Cost Path tool in ArcMap 10.2.2 to determine distances from sample collection sites of potential paths travelled to the MPA; Cost Path calculates a least-cost path between a destination and source location, fixing land as a boundary to movement. To create potential paths based on where lobster could move within the sampling area I generated 100,000 random points within the EPLMA boundaries and built Thiessen polygons. I then converted the polygons to lines and, using the Network Analyst and Make Closest Facility tools, generated distances in meters between each collection site and to the closest MPA boundary within the MPA islands (Figure 2).

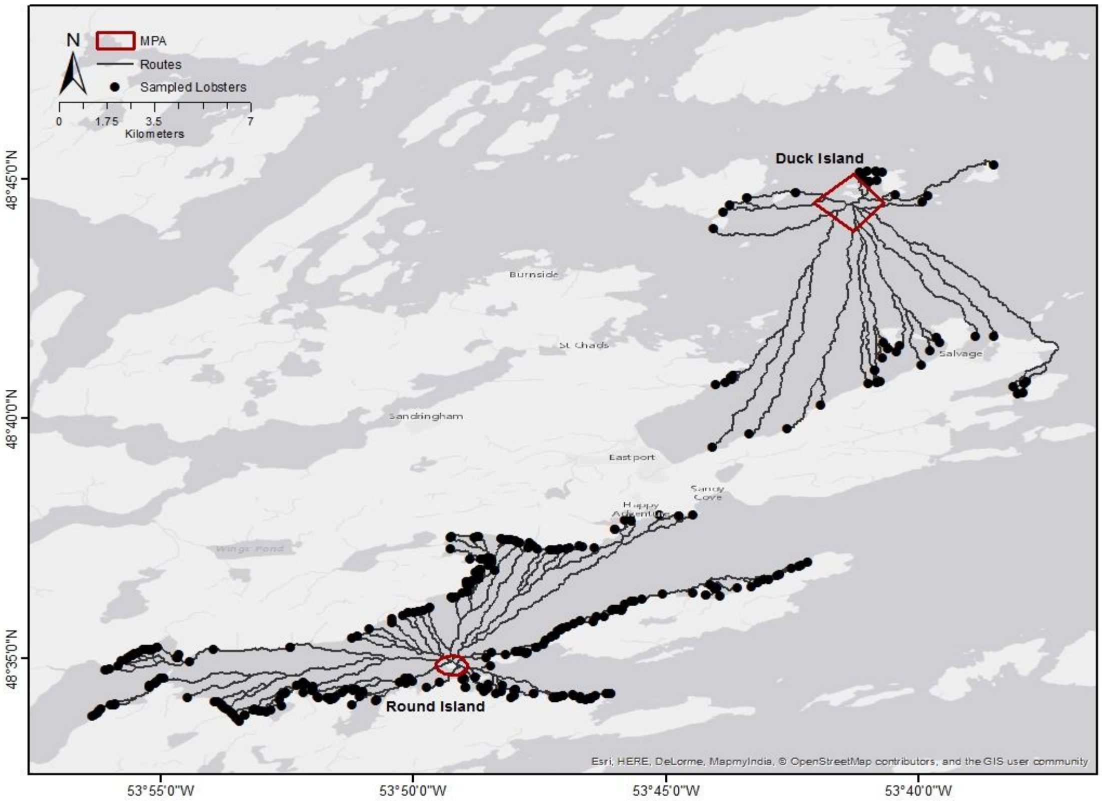

Figure 2: Least distance routes generated along Thiessen polygons to determine distance between sampling locations and nearest MPA Island. This method follows the sides of polygons in generating distances, thus avoiding use of straight lines that cross over land.

2.2.5 Generalized Linear Model

Two sets of Generalized Linear Models (GLMs) were used to relate the impact of distance to the MPA on fecundity at length. One set of models used the full dataset, whereas the second used a data set filtered to an area within 2 km of the MPA boundaries. In all models I used a gamma error structure with a log link function as the distribution of the response variable. Comparisons of the models within these two data sets, including the null model (Fecundity ~1) used likelihood ratio tests.

$$T = -2Log\left(\frac{\mathcal{L}_s(\hat{\theta}|x,g)}{\mathcal{L}_g(\hat{\theta}|x,g)}\right)$$

where T is the test statistic, Ls is the likelihood of the null model with parameter estimates $\widehat{\theta}$ given data x, and Lg is the general model that includes explanatory variables, independently (carapace and distance) and their interaction. The GLM and likelihood ratio tests were generated using R version 3.3.1 with the 'glm' and 'logLik' packages (R Core Team 2016). For all models I verified the assumptions of normality and constant variance of the residuals.

2.2.6 Estimates of Fecundity

I compared size-fecundity relationships of American lobster available from previous research completed in a range of geographic locations from Canada and the United States, shown in Table 1. The size-based model assumed fecundity followed a power scaling relationship with length ($F=aL^b$), where F represents fecundity, a denotes the scaling factor, L is carapace length and b denotes the power exponent. Here I estimated scaling and power parameters, a and b, using a nonlinear least squares model for the combined sampling years (2013 and 2014). From this relationship, I estimated fecundity for a standardized size of 85 mm carapace length, the size class available for most models from the various geographic locations from Newfoundland, Canada to Massachusetts, USA (Table 1) (Currie et al. 2011). Confidence intervals were generated using the predictNLS function in R. I calculated fecundity estimates, standardized for an 85 mm carapace length, using the latitudinal model provided by Currie and Schneider (2011), in which:

$$F_{85} = 490.6Latitude^{-12222}$$

$$a = F_{85}/(L^b)$$

$$b=0.08597Latitude +7.0202)$$

based on the same variable abbreviations listed above. They established this relationship to quantify size-fecundity relationships in relation to geographic variation, and the latitudinal position of the Eastport MPA of 48.66 °N. In addition, I compared the Eastport fecundity-at-length curve to published estimates from around the Eastern United States and Canada.

Table 1: Parameter estimates a and b from non-linear fecundity equation of American lobster along the east coast of Canada and the United States as published by Currie and Schneider (2011).

Location	A	b	Reference
Northwest coast, NL, Canada	0.293255	2.39308	Ennis 1981
Boswarlos, West Coast, NL, Canada	0.001862	3.49668	Ennis 1981
Arnold's Cove, Placentia Bay, NL, Canada	0.002641	3.47012	Ennis 1981
Paradise, Placentia Bay, NL, Canada	0.0533	2.78993	Ennis 1981
Northumberland Strait, NS, Canada	0.000542	3.77922	Campbell & Robinson 1983
Eastern Nova Scotia, NS, Canada	0.000251	3.9592	Campbell & Robinson 1983
Bay of Fundy, NS, Canada	0.007236	3.19005	Campbell & Robinson 1983
Southern Gulf of Maine, MA, US	0.001443	3.49574	Estrella & Cadrin 1995
Cape Cod, MA, US	0.006338	3.21765	Estrella & Cadrin 1995
Buzzards Bay, MA, US	0.000523	3.75921	Estrella & Cadrin 1995

2.2.7 Lobster Egg Production near the MPA

I used estimates of density (Lewis et al. 2017), sex ratio, and size structure of lobster sampled both inside and outside the MPA (from DFO mark-recapture data) in conjunction with a size-fecundity relationship to estimate egg production from lobster inside the MPA. The MPA monitoring program includes an annual mark-recapture program that occurs throughout the EPLMA and inside the MPA boundaries. Lobster tagging occurs in the fall of the year and is conducted with lobster caught in both commercial and experimental pots to obtain a broader size distribution than either gear alone. DFO tags lobster inside and outside of the Eastport MPA throughout the entire EPLMA, and records carapace length, sex, reproductive status, and the presence/absence of a v-notch for all tagged lobster (DFO 2013). From 1997-2011, 16,341 lobster were tagged or recaptured, 9854 inside the MPA and 6487 outside the MPA. In order to estimate egg production inside and outside the Eastport MPA, I developed a simulation model by extrapolating lobster abundance from the product of density estimates of lobster from Lewis et al. (2017) and the surface area of the entire MPA (2.1 km^2) or the EPLMA (400 km^2). Annual mark-recapture data from DFO (collected inside and outside of the MPA from 1997-2011) provided a size-frequency estimate. I then simulated egg production for each year inside and outside the MPA by multiplying the estimated abundance by the proportions at size, and sex ratios obtained from the mark-recapture data. Egg productivity was then calculated according to the size-fecundity relationship, described in section 2.3.4 of this chapter, for each female lobster in the distribution. I compared inside versus outside as the percent difference in egg production. To account for differences in sampling intensities I resampled (with replacement) the length frequency distributions 1000 times to create distributions of productivity inside and outside the MPA for each year from 1997-2011.

2.3 RESULTS

2.3.1 Berried Female Samples

Berried female carapace lengths from 2013-2014 ranged from 68 to 151 mm through the EPLMA based on 366 individuals, the majority of which were commercial-sized lobster (82.5mm CL) (Figure 3). Sampling occurred during the fishery, so trap restrictions limited the potential capture of undersized and jumbo lobster (>120 mm). Size-fecundity relationships analyzed with a non-linear regression showed little difference in slope between Duck Island and Round Island (Figure 4), but with a slightly higher intercept for Duck Island. These results are based on only 49 individuals at Duck Island compared to the 317 individuals from Round Island. Both relationships had similar R^2 values, with 0.55 for Round Island and 0.56 for Duck Island.

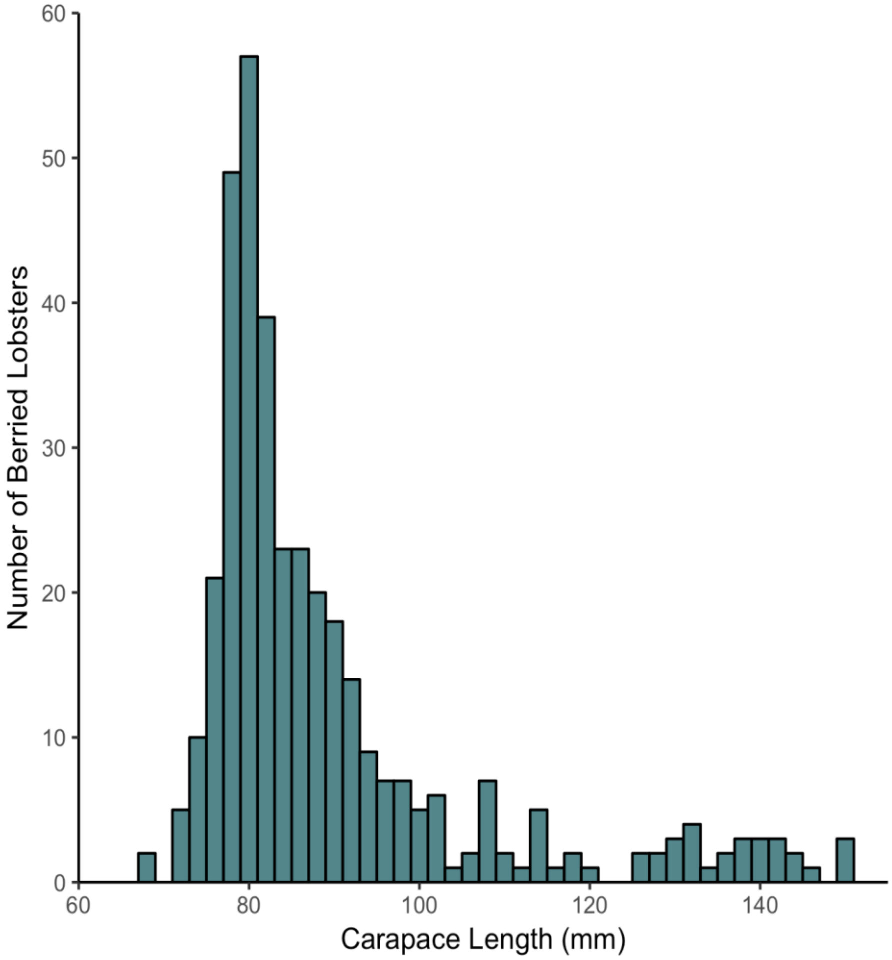

Figure 3: Distribution of berried female carapace lengths captured in commercial traps throughout the EPLMA (n=366).

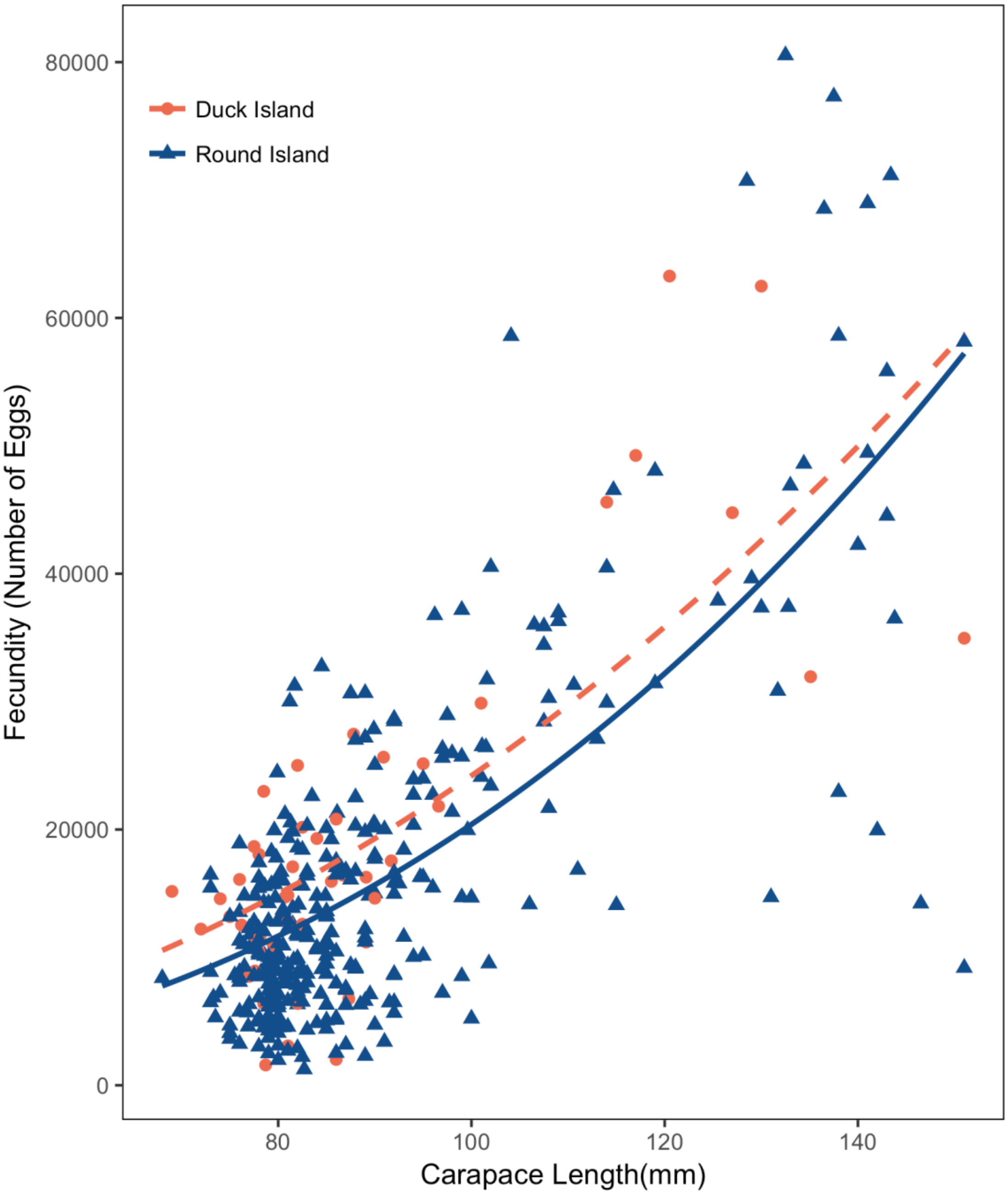

Figure 4: Relationship between estimated fecundity and carapace length of berried female lobster sampled around Duck Island and Round Island. Duck Island: a=1.19 (0.33 and 10.15 95% CI), b=2.15 (1.69 & 2.62 95% CI), r^2=0.56, and n=49; Round Island: a=0.20 (0.07 & 0.55 95% CI), b=2.50 (2.29 & 2.72 95% CI), r^2=0.55, and n=317.

2.3.2 Quantifying Sample Distance

Sampling followed the coastline, reflecting fishing activity in the Eastport Peninsula Lobster Management Area. I found no clear trend in lobster size or fecundity of berried females in relation to distance from MPA boundaries (Figure 5).

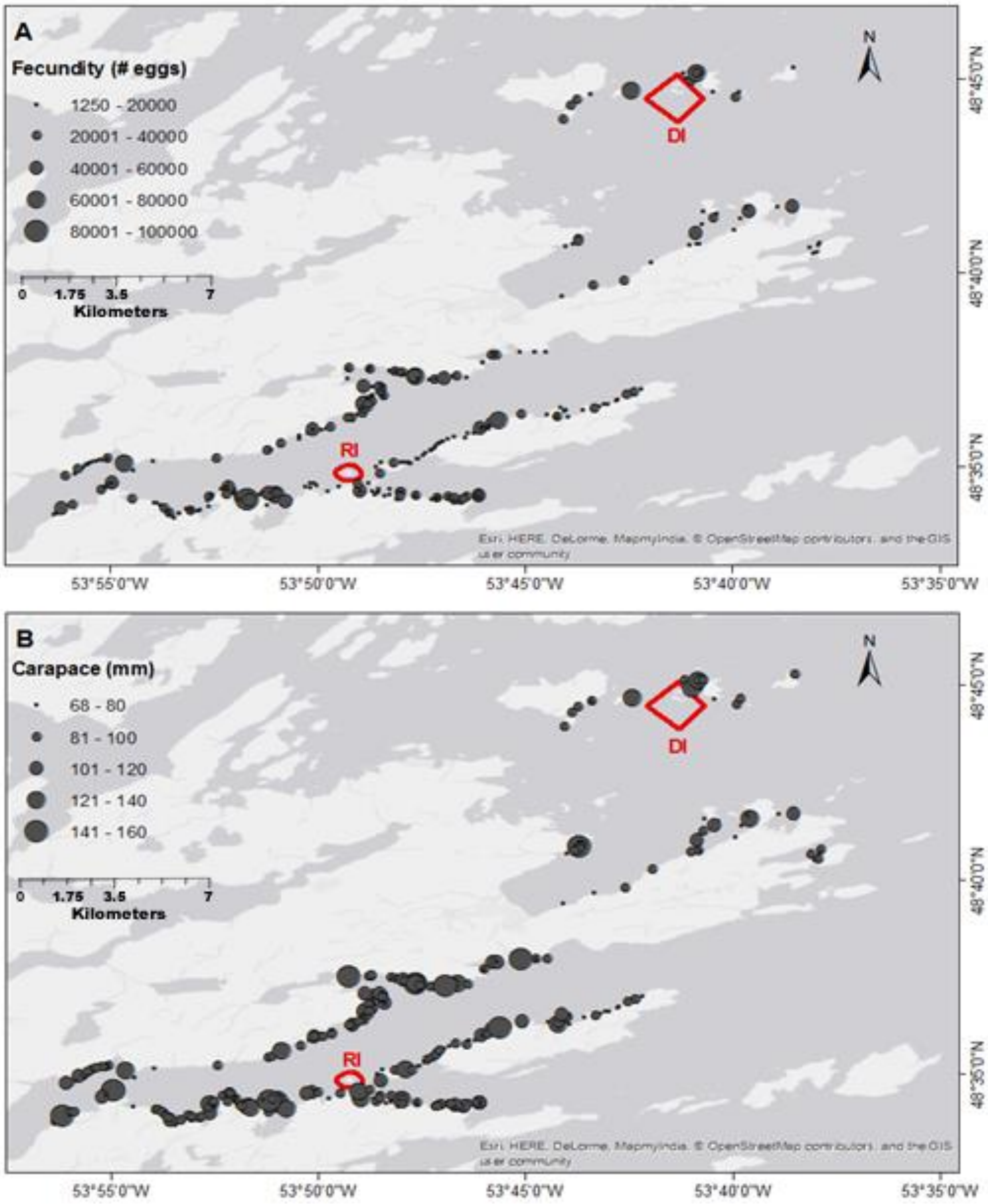

Figure 5: Female berried lobster samples in EPLMA represented by estimated fecundity (A) and carapace sizes (B) of 366 individuals

2.3.3 Size Gradients

The addition of carapace length improved the fit of the Generalized Linear Model (GLM), but adding distance from the MPA did not, either as an additive or an interactive variable for both data sets (refer to AIC and T values in Tables 2 and 3). Fecundity decreased slightly with increased distance from the MPA (Figure 6). Carapace size decreased slightly with increased distance from the MPA (Figure 6). Results from the likelihood ratio test suggest that distance did not improve model fits for either data set (T <3) (Tables 2 and 3).

Table 2: Fecundity estimates in relation to distance and carapace length from the MPA throughout the entire Eastport Peninsula Lobster Management Area. Variables presented as F (fecundity), C (carapace length), D (distance from nearest MPA boundary), AIC (Akaike Information Criterion), T (Likelihood Ratio Test Statistic). * denotes the interaction term.

Full Data Models	DF	Parameter	Estimate	t-value	AIC	T
F ~ 1	383	Intercept	9.72711	238.9	8150	
F ~ C	382	Intercept	7.163825	53.07	7897.1	254.4743
		C	0.027186	18.40		
F ~ D	382	Intercept	9.838e+00	118.055	8148.7	2.942495
		D	-2.070e-05	-1.552		
F ~ C+D	381	Intercept	7.231e+00	50.299	7897.7	255.8652
		C	2.707e-02	18.313		
		D	-1.050e-05	-1.271		
F~C*D	380	Intercept	6.956e+00	25.329	7898.7	256.8776
		C	3.015e-02	10.057		
		D	4.037e-05	0.921		
		C*D	-5.735e-07	-1.191		

Table 3: Fecundity estimates within two kilometers from boundaries of the MPA. Variables presented as F (fecundity), C (carapace length), D (distance from nearest MPA boundary), AIC (Akaike Information Criterion), T (Likelihood Ratio Test Statistic). * denotes the interaction term.

2km Models	DF	Parameter	Estimate	t-value	AIC	T
F ~ 1	29	Intercept	9.8523	66.86	645.38	
F ~ C	28	Intercept	6.952938	22.077	604.18	43.20286
		C	0.029358	8.833		
F ~ D	28	Intercept	9.5729007	13.705	647.06	0.3261546
		D	0.0001866	0.406		
F ~ C+D	27	Intercept	6.875e+00	15.963	606.08	43.30799
		C	2.920e-02	8.691		
		D	6.228e-05	0.316		
F~C*D		Intercept	9.686e+00	7.108	603.73	47.65724
		C	1.531e-03	0.115		
		D	-1.905e-03	-2.043		
		C*D	1.937e-05	2.133		

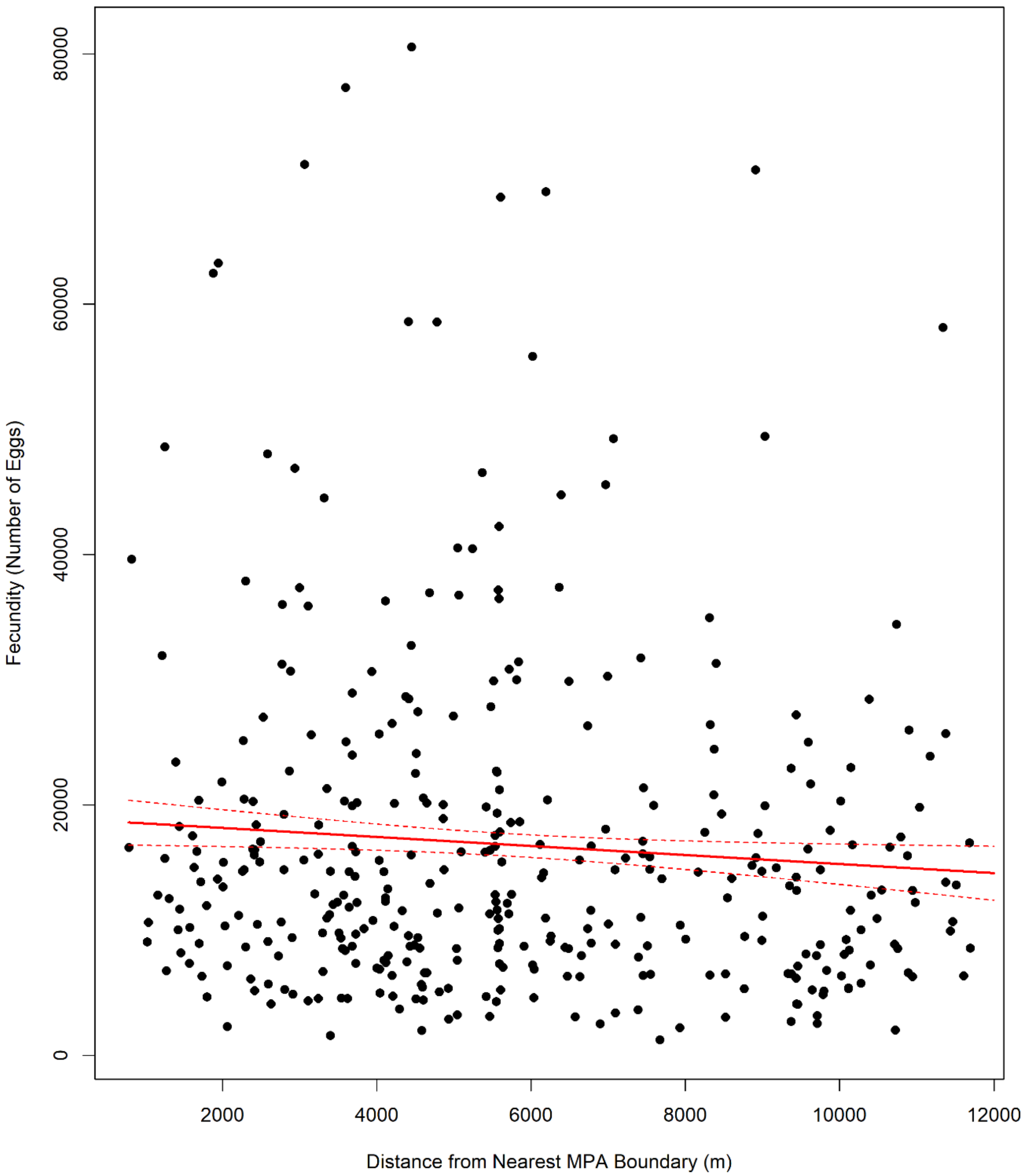

Figure 6: Fecundity of berried females in relation to distance from nearest MPA boundary. Red solid line shows the linear model (fecundity ~ carapace * distance) fit to lobster with a mean carapace size of 89.7 mm, with 95% confidence interval bands (red dotted lines).

2.3.4 Comparison of Fecundity Estimates and Regional Variation

I estimated mean fecundity for females at 85 mm *CL* around the Eastport Peninsula using two different methods. The 95 % confidence intervals overlapped substantially (Figure 7), showing no significant difference between the fecundity estimates using the standard model ($F=aL^b$) based on field samples or the general latitude model ($F_{85} = 490.6Latitude^{-12222}$). To investigate potential fecundity similarities with other American lobster populations, I plotted the Eastport fecundity-at-length curve alongside curves from Atlantic Canada and New England, including Newfoundland (Northwest Coast, Boswarlos (western Newfoundland), Arnold's Cove (southern Newfoundland), Paradise (eastern Newfoundland), the Canadian Maritimes (Northumberland Strait, Eastern Nova Scotia, and Bay of Fundy) and New England (Southern Gulf of Maine, Outer Cape Cod, and Buzzards Bay) as published by Currie and Schneider (2011). Although not supported by statistical analysis, and instead relying on published studies, the fecundity of Eastport lobster appeared to be higher at lower carapace lengths (<85 mm) compared to the other regions (Figure 8, noting that for all areas except Eastport, researchers determined fecundity by stripping all eggs).

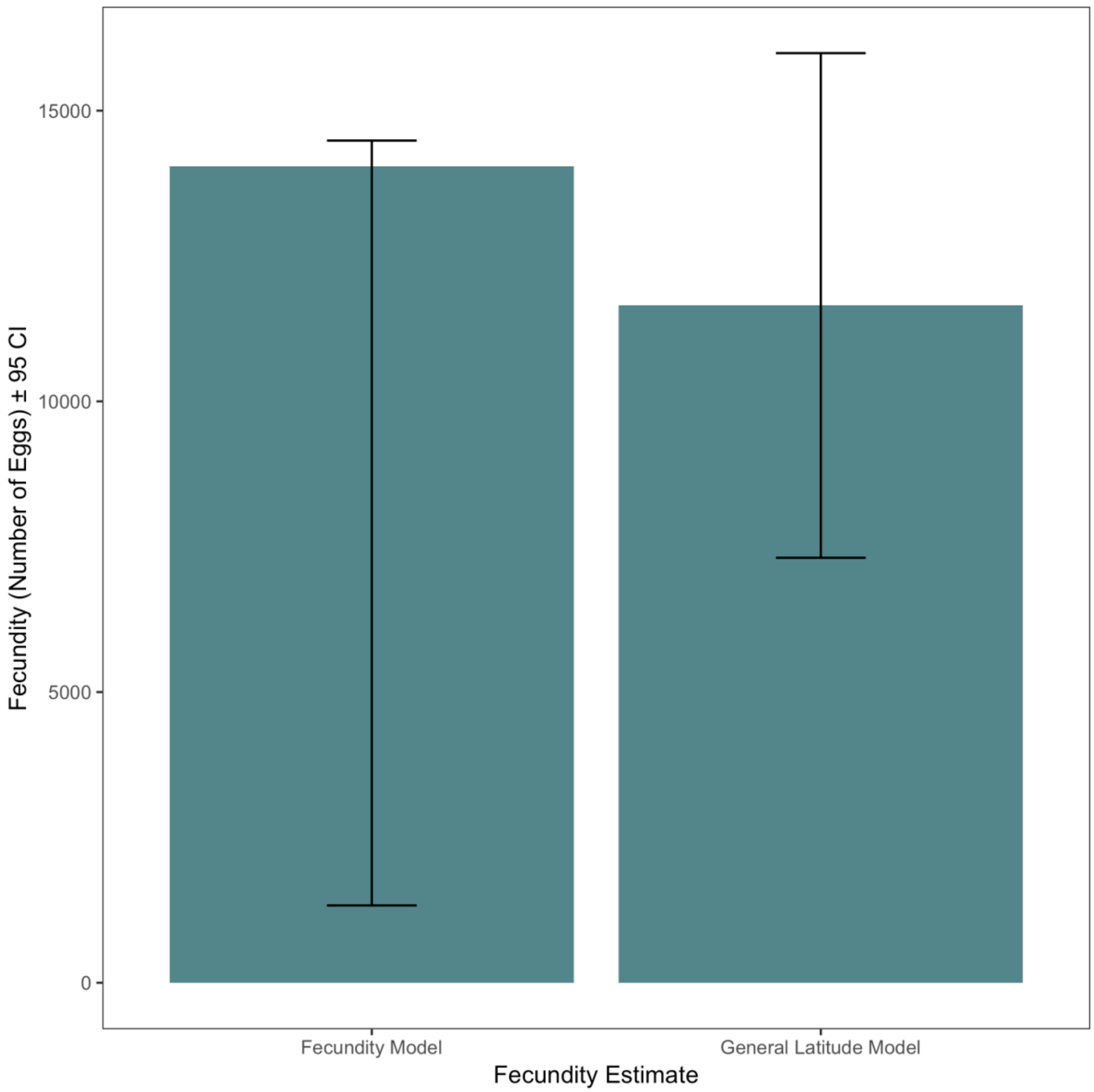

Figure 7: Mean fecundity estimates from two methods of modelling for female lobster (at 85 mm) in the Eastport Peninsula Lobster Management Area; lines denote 95% confidence intervals.

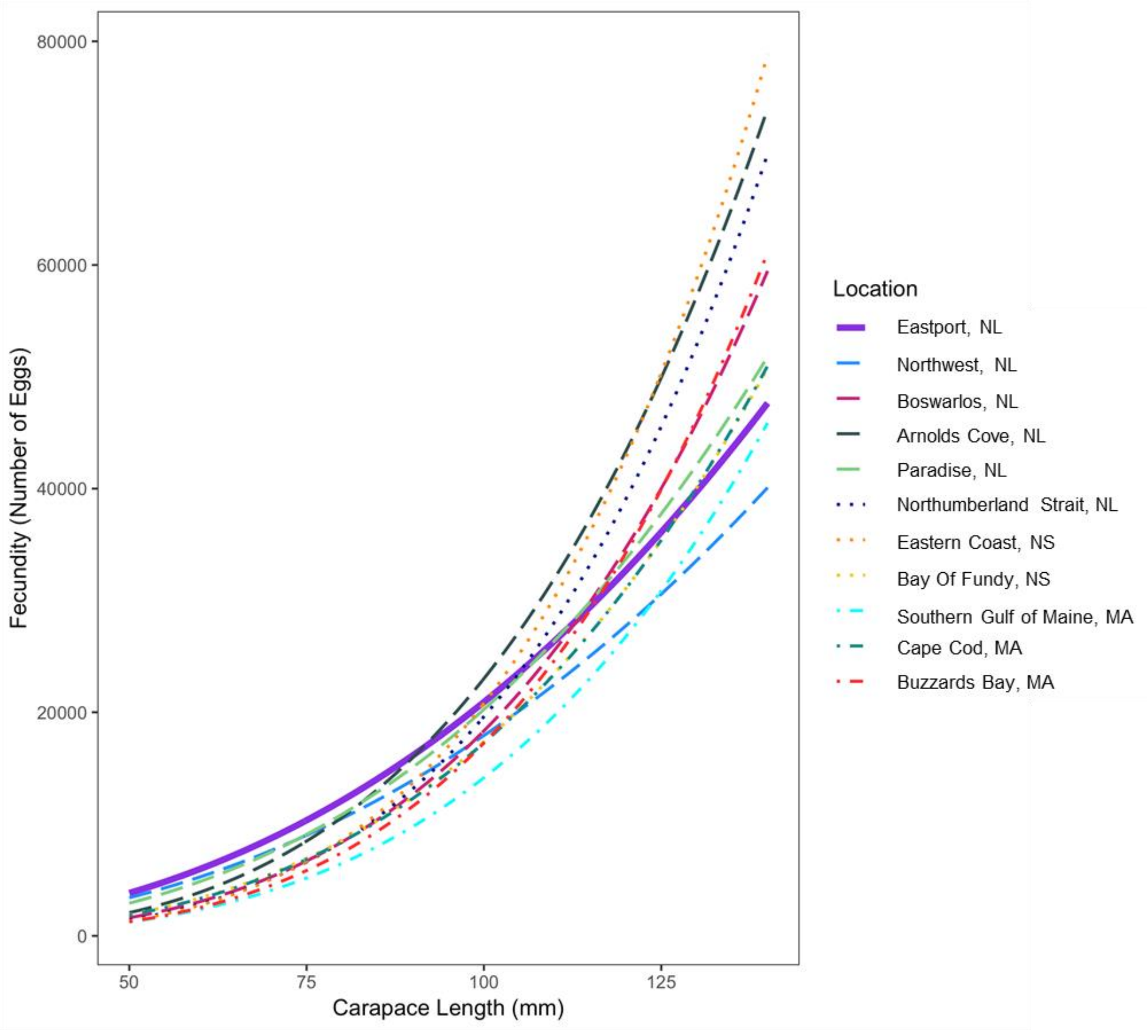

Figure 8: Nonlinear fecundity at size comparisons of Eastport female lobster to lobster in Newfoundland, the Canadian Maritimes, and New England locations based on published estimates by Currie and Schneider (2011).

2.3.5 Egg Production Estimates

I found highly variable production during the monitoring period (1997-2011), averaging 39.9%· year^{-1} (± 12.4 % SE) excess production from within the MPA compared to a non-protected area adjacent to the MPA. Estimated excess production in the MPA exceeded an equivalent-sized area outside the MPA in all years except 2000, 2002, and 2010.

Small differences between lobster densities inside and outside the MPA and an overall higher percent female outside the MPA (Figure 9) may explain those anomalous years. Although MPA egg production represented a small fraction of the total estimated median production for the EPLMA (0.002%· $year^{-1}$ ± 0.0007% SE) on a per km^2 basis, the MPA yielded an above average contribution producing 0.74%· $year^{-1}$ ± 0.22% of total EPLMA eggs from an area of 0.53% of the total EPLMA.

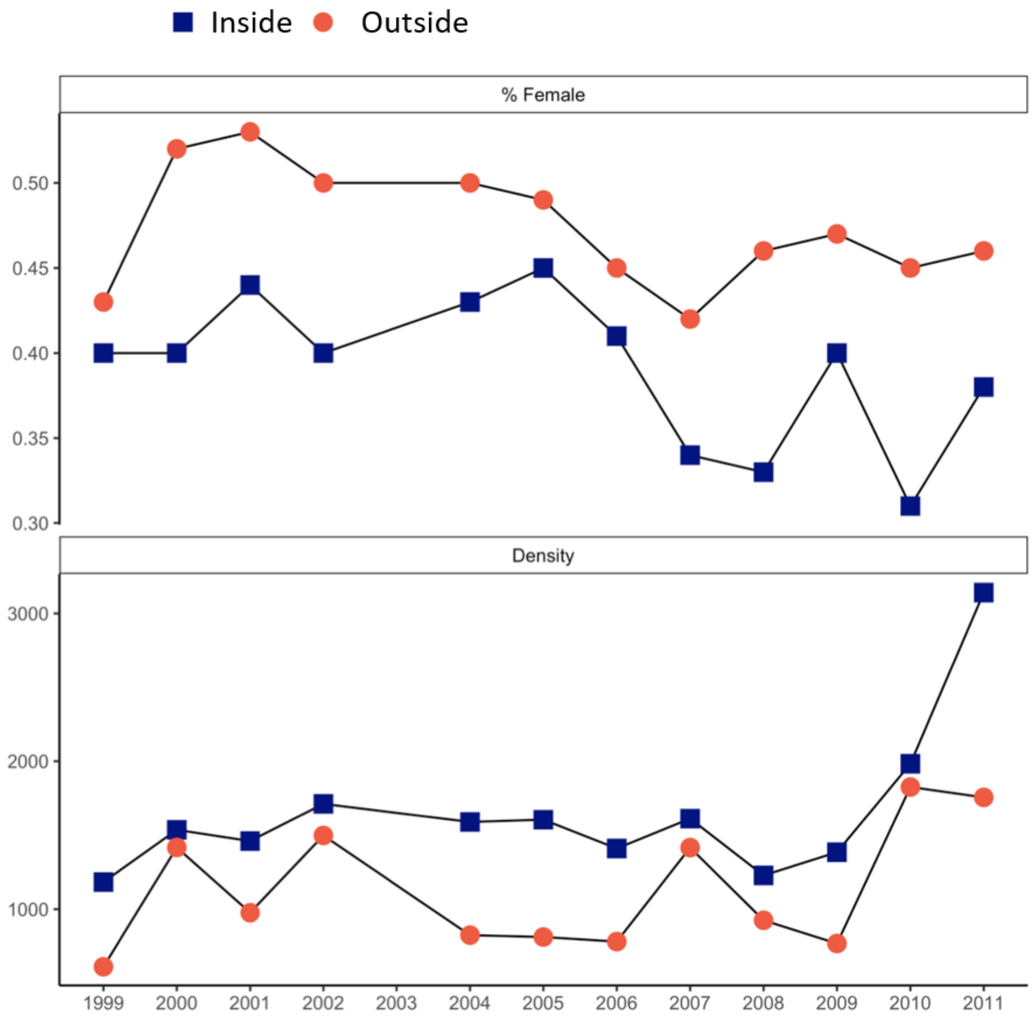

Figure 9: Monitoring statistics for the Eastport MPA and reference area detailing sex ratio from the mark-recapture data and density scaled to number of lobster per km^2 (Lewis et al. 2011). Lobster inside the MPA shown in orange circles and lobster outside the MPA as blue squares.

2.4 DISCUSSION

My study found no evidence of a spatial trend in the fecundity of female lobster in relation to the boundary (Figure 6) of the Eastport Marine Protected Area. Using Generalized Linear Models to describe the relationships between size, fecundity, and distance, I found no increase in fit when adding distance as a parameter, as shown through the likelihood ratio test (Table 2). When modelling local fecundity of lobster, I found no difference between the standard fecundity model based on fecundity samples from the field, and the fecundity estimate from a general latitude model developed by Currie and Schneider 2011 (Figure 7). Comparing the local fecundity curve of lobster in Eastport to other populations throughout Canada and the United States, Eastport lobster appear to have a greater fecundity at lower carapace lengths (Figure 8), highlighting the potential for different fecundity estimates among populations and the importance of obtaining local estimates. To quantify the reproductive contribution of the Eastport MPA in relation the surrounding management area I estimated egg and surplus production. I found that production was highly variable throughout the monitoring period and that the MPA produced $0.74\% \cdot \text{year}^{-1} \pm 0.22\%$ of total EPLMA eggs, averaged over all years.

Lobster size gradients around the MPA

I chose a gradient design to explore the impact of the MPA proximity on the fecundity of lobster in the Eastport Peninsula Lobster Management Area. The gradient design allowed me to measure the MPAs potential impact on larger berried females without requiring the removal of eggs from berried females inside the MPA boundaries. Distance from the MPA had no clear effect on carapace size or the fecundity of female lobster. Data collection resulted from a collaboration with fishermen during the fishery, which meant lobster could not be sampled inside the MPA boundary. However, given the relatively small size of the MPA components and the conservative home ranges estimated for American lobster (estimated dispersal of 13 km^2 per week on average in Northumberland Strait; den Heyer et al. 2009), I believe that the addition of data inside the boundary would unlikely change the interpretation significantly. Past research from Janes (2009) and Collins (2010) on lobster in Eastport reported higher percentages of large lobster and significantly higher carapace lengths inside the protected area than outside of the closure since its establishment, and the mean sizes of males and female lobster increased inside the MPA sites over time. These findings supported the decision to examine the potential impact of the MPA on fecundity and size but the results from this study did not support the conclusions in Janes (2009) and Collins (2010). Differences in sample size between this study and previous research, or measurement error, may have contributed to the discrepancies between results on the impact of the MPA on female lobster. Janes (2009) sampled 1124 females inside the MPA of 4078 total lobster, and Collins (2010) sampled 2311 females inside the MPA of 8743 total lobster. This study was limited to only 366 total samples of female lobster outside the MPA. Timing of sampling also varied between projects, both Collins (2010) and Janes (2009) used data from the fall tagging program that occurs annually as part of the MPA management and monitoring program (DFO 2007). Sampling for this project occurred during the fishery in the spring of 2013 and 2014. Seasonal variation could contribute to differing results resulting from changes in lobster movement, noting that American lobster movement strongly correlates with temperature (Aiken and Waddy 1986; Chang et al. 2010).

Distribution of lobster often varies throughout the year, in that Gulf of Maine lobster migrate inshore in the spring and to deeper waters in the fall, and lobster in New Hampshire move into estuaries in the spring and towards the coast in the other seasons (Chang et al. 2010). In the Northumberland Strait individuals travelled a mean distance of 10.8 km between mark and recapture, and movement rates decreased in colder months (December to April). The differences in my results from previous research in the Eastport MPA may partly reflect the timing of sampling and variation in water temperature at those times.

Limitations and sampling bias

The absence of any pre-closure data precluded a preferred Before-After-Control-Impact approach, whereas a gradient approach provided a mechanism to consider distance from the closure in the analysis. Current regulations allow landing of all non-egg bearing lobster larger than 82.5 mm in the commercial lobster fishing area (LFA 5) location of the MPA (DFO 2014). My study could not include individuals from size classes too large for commercial traps to sample effectively. Collaborating with commercial harvesters required sampling from baited traps which can result in a sampling bias associated with lobster catchability (motivation to enter a trap). Factors that impact catchability include temperature, size, sex, reproductive status (berried or not), habitat, feeding status and intra- or interspecific interactions (McLeese and Wilder 1958; Miller 1995; Tremblay and Smith 2001). Catchability tends to increase with lobster carapace size, to a point, where it then plateaus or decreases, however, this is not always the case because areas without an abundance of large lobster have a higher recapture rate for smaller lobster (Miller 1989; Miller 1995). Tremblay et al. (2006) found that berried females were more catchable than non-berried females, which may reflect the more aggressive behaviour of berried females, and that interactions between lobster outside of traps tend to reduce catch rates (Richards et al. 1983). Environmental factors also merit consideration; temperature greatly impacts the locomotion of lobster, in turn, contributing to catchability, particularly below 12° C (McLeese and Wilder 1958; Jury at al. 2013). Varying habitat types also motivate lobster movement; sampling conducted at sites with boulders resulted in lower catchability (even with higher lobster density), likely reflecting differences in hydrodynamics and the dispersal of bait odours along with the greater availability of shelter from boulders (Tremblay and Smith 2001). Without monitoring bait used, habitat type, bottom temperature, and noting other factors such as trap fullness (species caught and their sizes), I cannot differentiate which of these factors may have impacted sampling among trap locations for this study. However, all of these intrinsic and extrinsic factors can potentially influence lobster catchability or which lobster are sampled in this case. Based on the results from the studies noted earlier, larger, berried females could potentially experience higher catchability than smaller females. However, the individuals sampled in this study (68 -151 mm carapace length) encompassed a typical range for reproductive-sized lobster (50 mm to 150 mm carapace length (Haar et al. 2017)). Sampling bias from catchability factors may still have skewed the size and prevalence of where I captured berried females within the EPLMA. Sampling effort focused disproportionately within 12 km from MPA boundaries because sampling depended on cooperation with fishermen; this bias potentially masked a fine-scale gradient in fecundity with distance from the MPA. The habitat surrounding the MPA may limit a spillover effect because habitat discontinuity may inhibit outward movement of settled lobster (Di Lorenzo et al. 2016). When lobster settle from a pelagic to benthic stage, they rely heavily on shelter from crevices, large cobble, and boulders, and forage in adjacent habitat (Lawton and Lavalli 1995 and Selgrath et al. 2007). The reliance of lobster on specific habitats such as complex rocky bottoms support the importance of habitat continuity across the MPA border for settled juvenile or adult spillover to occur (Novaczek et al., 2017). The pelagic stage of a lobster life cycle also poses a challenge in detecting benefits of the MPA because larvae reside in the water column for up to 6 weeks and many (likely) drift out of the fishing area. Dispersal studies suggest that lobster larvae in the North Atlantic travel large distances from their source location (Inzce et al. 2010).

Estimating Lobster Fecundity

I compared two methods of estimating the fecundity of lobster. First, I used, the widely used two-parameter power function (Saila et al. 1969) with data collected through the non-invasive technique to estimate individual fecundity (Currie et al. 2010). I then compared that result with a latitude-based model established by Currie and Schneider (2011). I found no significant difference between these two methods. The first approach uses the non-invasive egg measurements to estimate clutch size, which feeds into the power function ($F=aL^b$). The second approach incorporated latitude of the target location to estimate the fecundity of local lobster, a method established to quantify variation among lobster from different locations across its commercial range (Currie and Schneider 2011). A third approach, not tested in this study because of its unpopularity with local fishers, measures fecundity of lobster by fully stripping the clutch and counting eggs directly.

Plotting average fecundity-at length of local female lobster in the EPLMA alongside fecundity estimates throughout the species range indicated a relationship in EPLMA lobster comparable to populations around Newfoundland, the Canadian Maritimes, and as far south as New England. At 85 mm, Eastport Lobster had the highest fecundity-at-length relative to more southern locations. Eastport lobster also have higher fecundity-at-length at sub-legal sizes than locations at lower latitudes. The purpose of this analysis was to highlight variation among lobster populations and to demonstrate the need for local estimates. The locations included in Figure 8 encompass a variety of thermal profiles, from the northern locations (Eastport and Canadian Maritimes) with colder, well-mixed regimes to warmer, summer-stratified regimes (New England) (Bergeron 2011). Temperature is a major factor in the development and release of lobster eggs, and in individual growth (Aiken and Waddy 1986). Temperature primarily controls the size of maturity, maturation of eggs, and the timing and synchronization of spawning and hatch time. Temperature plays such a vital role in spawning that the associated time frame can vary by months, depending on the geographic location of the lobster (Waddy et al. 1995). Cold water lobsters grow more slowly (Waddy et al. 1995) and experience a delay in maturation and therefore produce more eggs at smaller sizes from the longer periods between spawning. At larger sizes, fewer eggs per individual reflect the shorter growing season and reduced energy gain and storage in colder waters (Waddy and Aiken 1995). This interpretation may explain the higher fecundity-at-length in smaller lobster as shown in Figure 8 by the Eastport population, an effect of the geographic location rather than an outcome of the establishment of the MPA.

Lobster egg production estimates

I estimated egg production based on measures of local fecundity-at-size scaling rates, yearly estimate sex ratios, and size distribution of the population and concluded that the

MPA, based on these variables, would produce 0.74%· year^{-1} ± 0.22% of eggs per year of the entire EPLMA (400 km^2). Across all years, the percentage of female lobster on average tended to be greater outside than inside the MPA. This observation could result from several factors, however, the most likely factor is the exploitation outside the MPA, where males are more likely to be captured and females are partially protected (v-notched and berried individuals not retained), thus skewing the estimated sex ratios from post-harvest monitoring. Female lobster receive protection from harvesting when they are berried or v-notched, and both male and female receive protection from fishing activity inside the MPA boundaries. In addition, lobster captured in the fishery along the MPA border and subsequently released (berried females, v-notched, or sublegal lobster) may experience increased stress from handling resulting in increased movement. Past studies reported a higher proportion of berried females and larger females inside the MPA (Janes 2009; Collins 2010) as well as a higher mean size of male lobster inside the MPA boundaries compared to adjacent fishing grounds (Janes 2009). However, the relatively limited space protected by the MPA could mute any signal of surplus production through protection. Overall, the estimated per unit egg production is related to estimated lobster density inside and outside the MPA, which itself tends to vary without trend over time. However, I observed positive estimates of surplus production in 9 of the 12 years where data was available, a finding consistent with Xu and Schneider (2012) who reported that the MPA would increase the reproductive value of the local stock. The MPA makes up less than 1% of the LFA size and 0.53% of the EPLMA, and I estimated that it only accounts for 0.74% of the net egg production for the surrounding EPLMA. Though the MPA itself does, on average, appear to increase productivity within its boundaries, this surplus production represents just a small fraction of overall MPA productivity and is less than the year-to-year variability in realized or estimated lobster density. The local industry implemented v-notching around the same time as the MPA designation, complicating efforts to evaluate the contributions of the MPA at a large scale. Throughout the American lobster range, few studies regularly monitor egg production, and studies typically estimate fecundity from berried female abundance and a general size-fecundity relationship, without considering geographic variability in this relationship (Tang et al. 2018).

Benefits of MPAs

Marine Protected Areas can provide multiple benefits to marine ecosystems including protection of biodiversity, provision of resiliency, and potential spillover to unprotected areas resulting from increased productivity. Measuring potential benefits to a fishery surrounding an MPA can be challenging, particularly for taxa with benthic adults that produce pelagic larvae, such as American lobster (Lawton and Lavalli 1995; Diaz et al. 2011). The small size of the Eastport MPA limits its potential contribution to lobster recruitment in the larger management area, although protection of large and berried females from intensive fishing effort likely improved the overall productivity of the system, noting that past studies identify interactions with fishing gear as a significant source of mortality on brooded eggs. Lobster fisheries closures in Newfoundland were recommended by the Fisheries Resource Conservation Council (FRCC) in 1995 as a measure to assist in the reduction of exploitation of the resource to allow an increase in egg production, in addition to the protection female lobster have from v-notches and berried status (Ennis 2011). Once established as a closure the primary conservation goal of the Eastport Marine Protected Area was to maintain a viable American lobster population through conservation, protection, and sustainable use of the resources and habitat (DFO 2013). When exploring the contribution of the Eastport MPA to regional biodiversity and how it has met its conservation objectives, Novaczek et al. (2017) found the MPA provided a small refuge of suitable habitat for the local juvenile lobster within the fishing grounds and contained complex structures suitable for adult shelter. MPA proponents often promote potential increased egg production that could benefit surrounding unprotected waters, noting that indirect estimates exist for such a benefit for Eastport (*i.e.*, increased densities, larger size distributions, proportion berried: Janes 2009; Collins 2010; Lewis et al. 2017) but no direct estimates exist.

Previous studies to evaluate the efficacy of the Eastport MPA focused mainly on variation in population structure inside and outside the protected areas. By 2007, a higher percentage of legal sized lobster (≥82.5 mm) were reported inside both MPA islands compared to surrounding commercial areas (Janes 2009). From 1997 to 2007 the size distribution of females changed significantly. Berried females inside the MPA occurred in higher relative abundance than in surrounding areas, especially in individuals larger than 92 mm (Janes 2009). Mean sizes of both male and female lobster inside the reserves exceeded those in adjacent fishing areas (Collins 2010). The observation of a shift in size structure for American lobster within the MPA is consistent with the report of increased lobster size in protected areas globally (Lester et al. 2009). Previous research on the Eastport MPA, along with knowledge on lobster size specific fecundity, led me to expect larger, more fecund females closer to the MPA boundaries. Larger female lobster typically produce more eggs than smaller individuals (Aiken and Waddy 1980) and can produce both annual or biennial egg clutches at larger sizes (>120 mm CL) (Comeau and Savoie 2002; Waddy et al. 2012).

However, larger, more fecund females were not more prevalent within close proximity to the boundaries of the Eastport MPA.

Effective design and implementation of protected areas can play a major role in the success of conservation goals. Incomplete information on habitat and population structure prior to MPA implementation constrains evaluation of its efficacy. In the case of Eastport, conservation objectives were formulated at the scale of the larger surrounding EPLMA. At the time of establishment, stakeholders were seeking opportunities to increase egg production, and initiate spatial closures (eventually becoming an MPA) and the start of a v-notching program as simultaneous strategies to address this objective. V-notching, a non-lethal tagging method applied to any captured female, persists with females between molts and marks a reproductively active lobster as one that cannot be landed legally (Collins and Lien 2002). However, measuring and attributing any changes in the Eastport Lobster Management Area to either natural, broad-scale processes (*i.e.* temperature changes), v-notching, or the MPA itself is difficult. Moreover, even if the intrinsic variability of the system could be measured, understanding the relative benefits accrued by surplus production provided by the MPA or v-notching remains challenging.

With a combined protected area of 2.1 km^2, few scientists expected population enhancement throughout the entire 400 km^2 EPLMA region, as highlighted by Xu and Schneider (2012); indeed, the Eastport MPA makes up less than 1% of the surrounding Lobster Fishing Area (LFA). A measurable contribution to the population throughout the greater management area would require a much larger MPA. MPA design can draw on numerous criteria including size, location, species home range coverage, habitat representation, connectivity, balancing ecological and socioeconomic needs, among other biological, physical, and social factors (Pelc et al. 2010; Fox et al. 2012; Young et al. 2016; Pendred et al. 2016). As a small single-species protected area, the Eastport MPA protects a small area of potential lobster habitat for a species with widely dispersing pelagic larvae, with little pre-implementation data available to monitor success over time. The Eastport MPA was designed with a conservation objective to safeguard lobster spawning, rearing and feeding areas, and to maintain a viable lobster population (DFO 2007). Although I found no evidence of measurable spillover of mature females along the MPA boundary, a sufficiently enforced MPA could nonetheless provide a refuge in which lobster could rear, feed, and spawn.

The continued increase globally in MPA coverage provides ample evidence to support the use of small targeted MPAs. For example, the Bronte-Coogee Aquatic Reserve that covers only 0.43 km^2 in Sydney, Australia provides sufficient home range for large reef fish such as the Eastern blue grouper (Lee et al. 2015). The 0.25 km^2 Merri Marine Sanctuary in Southwest Victoria, Australia has also demonstrably enhanced a large and growing population of the benthic southern rock lobster (Young et al. 2016). Although I detected little surplus egg production in the Eastport MPA and could not separate the closure from other efforts (v-notching or increases in minimum legal size), such conservation actions can produce tangible benefits such as focused research attention, conservation ethic, local pride in management, and a protected population to aid in population studies of American lobster. Small, species-specific MPAs offer some major benefits, in that they can protect targeted habitats and their associated fauna and offer ease of monitoring and practicality in addressing threats to specific issues. The Eastport MPA makes up approximately 0.5% of the surrounding Eastport Peninsula Lobster Management Area; recognizing its potential contribution to the larger management area could support more successful monitoring and attainment of conservation goals (Stanley et al. 2015). The Eastport MPA accounts for less than 0.1% of the total egg production for the surrounding LFA, thus only marginally increasing regional egg production, noting the importance of spatial scale with respect to potential MPA efficacy (Xu and Schneider 2012). Without directed research (e.g. connectivity, spatial mortality) to determine potential benefits specific to the area, it is difficult to say whether an increase in MPA size would result in increased effectiveness. Multiple factors specific to the area including closure placement, habitat suitability and oceanographic processes would need to be considered. Successful lobster MPAs have demonstrated positive impacts on lobster fecundity and reproductive output when an increase in closure size occurred. For example the Columbretes Islands Marine Reserve in the Mediterranean Sea established in 1990 (initially 44 km^2 increased to 55 km^2 in 2009), has contributed to an increase in mean fecundity of spiny lobster (*P. elephas)* after 2 decades of protection. Occupying only 18% of the area, the reserve accounted for 80% of the region's egg production (Diaz et al. 2011). To address the Eastport MPA conservation goal of maintain a viable lobster population more effectively, monitoring should focus on recording changes in adult density inside and outside the MPA in order to identify any trends in egg production, and measures of size of maturity, with the goal of developing effective indicators that can be applied to American lobster populations along the northeast coast of Newfoundland.

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CHAPTER 3: INDICATORS FOR SUCCESS: INFLUENCE OF A MARINE PROTECTED AREA (MPA) ON INDIVIDUAL GROWTH RATE OF AMERICAN LOBSTER (*HOMARUS AMERICANUS*)

ABSTRACT

Fisheries managers have long used growth rates as a central statistic for decision making regarding harvesting size limits and as an indicator of population dynamics and productivity. As part of a monitoring strategy for the Eastport Marine Protected Area (MPA), Fisheries and Oceans Canada implemented a capture-mark-recapture (CMR) program to provide data to support estimates of population structure and movement. In order to evaluate growth rates in the Eastport region, I utilized size information collected from tagged individuals over a 16-year period (1997-2012). Female growth inside and outside remained steady over the tagging period in contrast to more variable male growth, with lower estimates from 2005-2012 down from the 1997-2004 estimates. There were no obvious differences between the growth of lobster inside and outside the MPA, however, when comparing the von Bertalanffy growth curves for female and male lobster a steeper curve characterized lobster outside the MPA than the curve estimated for inside the MPA. Measured growth rates were generally slower than those measured for populations throughout the species range. The CMR program provides a valuable and unique time-series for Newfoundland lobster science that demonstrates the importance of data collection prior to implementation of a MPA when evaluating the conservation outcomes. CMR data also provide an avenue for monitoring growth rates that can help to identify any unexpected changes in growth for the local population.

3.1 INTRODUCTION

Marine ecosystems around the world face pressure from fisheries driven by an ever-increasing demand for protein to sustain a growing human population. Habitat loss, overfishing, and climate change threaten the productivity, sustainability, food security, and biodiversity of marine systems (Green et al. 2014). The application of fisheries closures or Marine Protected Areas (MPAs) has gained increasing attention as a conservation tool for marine biodiversity, commercial species, and important or 'special' habitats, with global targets for protection set at 10% of the ocean by the year 2020 (Aichi Target 11). Often, managers seek to use MPAs and similar management interventions to boost targeted species abundance and/or biodiversity, and to provide a refuge for depleted stocks with hopes of curtailing over-exploitation or stock collapse (Green et al. 2014; Takashina and Mougi 2014; Krivan and Jana 2015). Globally MPAs protected ~3.7% of the oceans as of 2018 (Morgan et al. 2018), with regulations ranging from complete no-take zones to multi-use closures with varying regulations (UNEP-WCMC and IUCN 2019). The implementation and management of an MPA must ensure that it balances sound conservation measures with economic sustainability (Moeller and Neubert 2015), and the design and monitoring phases should consider both issues (Christou and Idels 2012).

To ensure that MPAs provide successful conservation and economic outcomes *(i.e.,* spillover or increased abundance), Robb et al. (2015) suggest configuring MPAs across a management seascape as a network of no-take closures managed through an ecosystem-based approach. At the individual site level, White et al. (2008) suggest that maximizing productivity and potential spillover from an MPA requires a reserve with a width equal to or less than the mean dispersal distance (including both larval dispersal extent and adult home range) of the targeted species. Few studies offer unambiguous evidence that MPAs benefit a given fishery, especially whether they increase productivity and recruitment. For an MPA to provide economic benefits, increased yields in remaining fishing locations must exceed lost fishing yields from the closed region. Increasing the per-individual yield or increased recruitment can produce this outcome (Hilborn et al. 2004). Marine reserves, along with other amendments to fisheries management, can build healthier ecosystems and support more sustainable fisheries (Barner et al. 2015). The success of a protected area in achieving these objectives links closely to its design, whereby the design must align with the biology of the targeted species. Effective design and monitoring outcomes post-implementation hinge upon understanding reproduction, dispersal, and recruitment.

Protected areas can potentially offer valuable data on an unharvested portion of a population. Long-term capture-mark-recapture experiments (CMRs), a common practice in MPA monitoring (Kelly et al., 2002; Goñi et al., 2006; Kay et al., 2012), can provide insights on species abundance, size structure, movement, habitat use, and sex ratios for species, while simultaneously helping to understand natural cycles of mortality, productivity, and abundance in a population with limited or no exploitation. Long-term CMR programs also add valuable population information such as growth (*i.e.,* molt frequency and size increment at molt in crustaceans), mortality, and size-at-maturity (Verdoit et al. 1999; Bevacqua et al. 2010 and Sundelöf et al. 2015). This information can offer significant value in developing robust stock assessments to guide fisheries management decisions.

Growth models commonly use age-at-length data to monitor the status of commercially exploited fish populations (Eaton and Link 2011). The absence of permanent calcified structures in American lobster and other commercially important crustaceans limit efforts to age individuals. New methods utilizing growth bands in the eyestalk and gastric mill could potentially provide this critical information (Kilada et al. 2012); however, few applications of direct aging exist, pointing to a need for further research before adapting these methods widely. Determining the age of lobster remains challenging because the molting process results in discontinuous growth (Chang et al. 2012). Temperature heavily influences molting, which typically occurs between late spring and early fall (Waddy et al. 1995). Juvenile lobster can molt as frequently as every month (or more), commercial sized lobster molt every 1-2 years, and large lobster (several kilograms) molting once every 4 to 5 years (Campbell 1983; Waddy et al. 1995). Egg production in mature female lobster reduces growth increment and molt frequency compared to mature males, which experience more rapid growth (Campbell 1983). Modelling life history traits such as lifespan, maturity, age at recruitment, and identifying cohorts requires growth estimates (Ricker 1975; Campbell 1983; Chang et al. 2012). Growth models and their parameters play a pivotal role in stock assessments for many commercial fisheries and thus directly influence scientific advice for fisheries management. These models can be used to determine age at recruitment or maturity, legal size limits, optimum yield, changes in population abundance and production (Chang et al. 2012; Raper and Schneider 2013). In the absence of information on age, researchers can implement length-frequency and tag-recapture programs to determine a continuous size-at-presumed age relationship based on the von Bertalanffy growth method (a generalised logistic growth curve based upon time-series data) (Chang et al. 2012). Catchability often limits growth estimates derived from mark-recapture studies to the size range typically captured in commercial traps; lack of knowledge on actual age of tagged individuals can thus limit interpretation of growth parameters (Fogarty 1995).

In 1995 stakeholders around the Eastport Peninsula, Bonavista Bay, Newfoundland formed the Eastport Peninsula Lobster Protection Committee (EPLPC), and in 1997 the group entered an agreement with DFO that only local fishermen could harvest lobster in the area. One of the EPLPC's conservation measures was the identification of two locations, Duck and Round Islands, as a voluntary no-take reserve (Collins and Lien 2002; Ennis 2011). The Eastport MPA received official status as an Oceans Act MPA in 2005. Since its establishment as a fisheries closure, an ongoing annual capture-mark-recapture program has sampled the focal species (American lobster - *Homarus americanus*) in waters both inside and outside the MPA, in order to monitor the growth, movement, and survival of lobster (Janes 2009). This CMR program takes place throughout the Eastport Peninsula Lobster Management Area, a 400 km^2 area within which the Eastport MPA is located (Figure 1).

Previous research on the lobster population in Bonavista Bay used logbook data and the CMR program (conducted inside and outside the MPA) to measure sex ratio, population size, number of fisheries recruits, movement, size-frequency, and average size. These studies demonstrated larger mean carapace lengths for males inside the closed areas than the adjacent fished area from 1997 to 2004, and that female mean size increased both inside and outside the MPA since 1997 (Janes 2009; Lewis et al. 2017). Since the establishment of the CMR program in the EPLMA, no estimates of growth rates have been produced for the Eastport lobster population. In order to estimate these rates, I estimated growth parameters of the local lobster population using methods adapted from Bevacqua et al. (2010) and data from the long-term CMR monitoring program. Using these data, I estimated the parameters of the von Bertalanffy growth model using only recapture intervals and growth increments between mark and recapture, rather than age data (Chang et al. 2012). Based on these analyses I evaluated whether the imposition of the MPA has detectably influenced growth rates, by comparing lobster tagged both inside and outside the MPA over the 16 years following the implementation of the EPLMA.

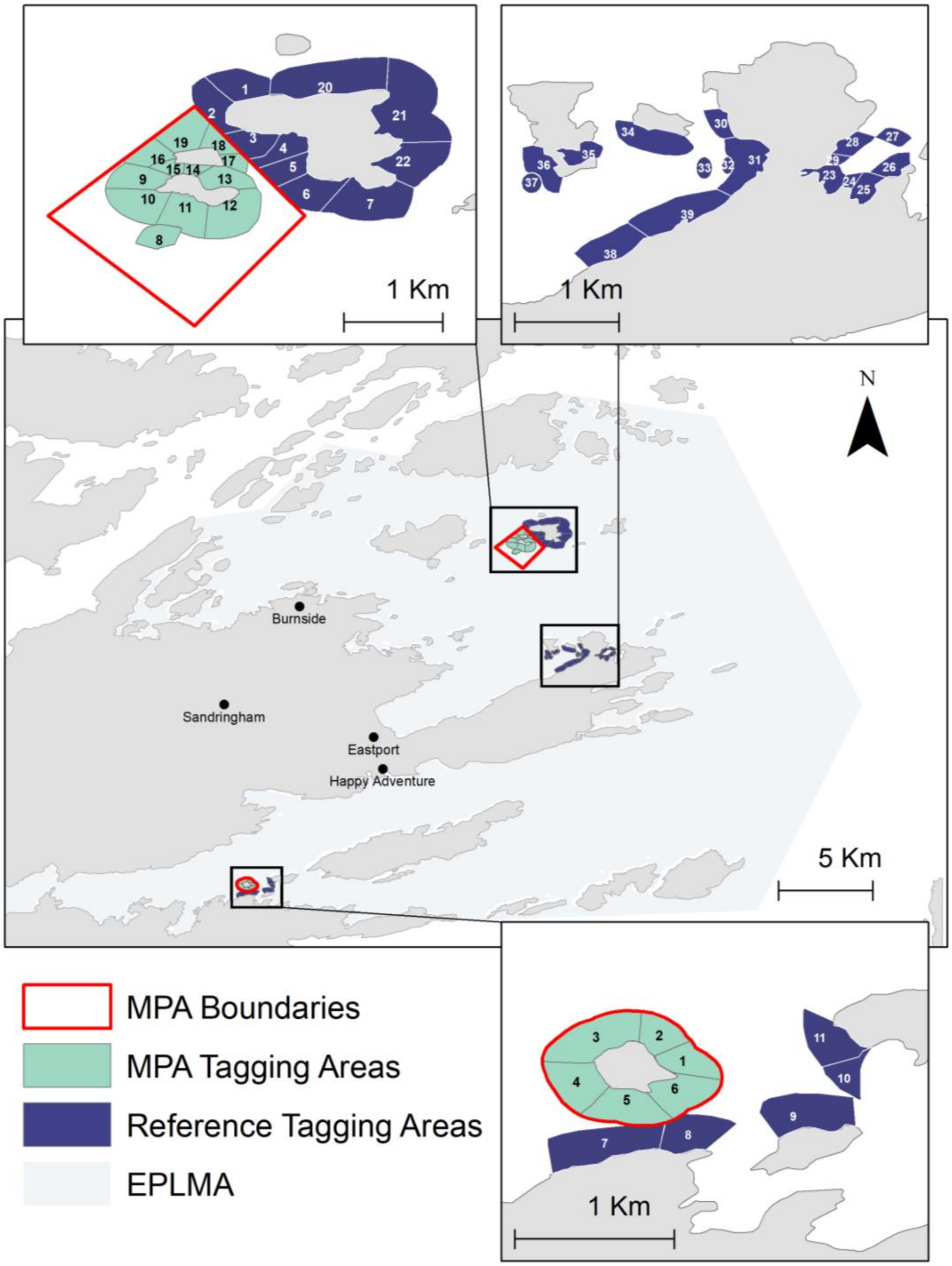

Figure 1: The Eastport Marine Protected Area within the Eastport Peninsula Lobster Management Area, Bonavista Bay, Newfoundland. MPA island boundaries shown with red line, green areas show where tagging occurred inside the MPA and purple areas show the tagging areas outside the MPA.

3.2 METHODS

3.2.1 Study Site and Data Collection

The Eastport MPA consists of two separate locations surrounding Duck and Round Island in Bonavista Bay, Newfoundland (Figure 1) that collectively span 2.1 km^2 around the two islands (Janes 2013). Fishers had identified these islands as prime spawning and rearing habitats for American lobster (DFO 2007). Regulations prohibit any fishing and human activities inside the boundaries of the MPA (DFO 2007). The Department of Fisheries and Oceans (DFO) ongoing CMR project on lobster provided the data for this research. The tagging project occurs in the fall, outside of the lobster fishing season. The program started in 1997 and occurs annually (excluding 2003) and is conducted inside and outside of the MPA (Figure 1), however, no location data is collected for trap deployment. From 2004-2010 two groups of harvesters deployed 100 commercial traps (50 traps per boat, 25 inside and 25 outside the MPA for each boat) to capture and tag lobster. In 2011 modified traps were added to the sampling protocol to retain very small lobster (under 70 mm) and very large lobster (over 125 mm). In more recent years the sampling evolved to include a total of 120 traps: 80 commercial traps are deployed with 60 outside and 20 inside the MPA, 40 modified traps are set with 15 small modified outside and 5 set inside, and 15 large modified outside and 5 inside. Figure 1 shows the areas used by harvesters during the tagging program as reference for sampling distribution. The traps are hauled daily (weather permitting) for a 3- to 5-week period. When lobster are captured, data are recorded on carapace length, sex, reproductive status, and presence or absence of v-notch. If the lobster is already tagged, the unique tag ID is recorded and any untagged lobster are outfitted with a polyethylene streamer tag, inserted dorso-laterally between the carapace and the first abdominal segment. The two-sided streamer tags have a unique ID printed on either side of the tag and are designed to be retained through molt cycles (Figure 2).

Figure 2: Streamer tag inserted dorso-laterally between the carapace and the first abdominal segment of adult lobster.

3.2.2 Data Structure

The Eastport CMR program tagged total of 10266 unique lobster between 1997 and 2012. I removed all lobster that exhibited zero or negative growth (indicative of errors in data recording or entry) and tags with inconsistent data (*i.e.,* inconsistent sex, males labelled as v-notched or berried) from the dataset. The remaining cleaned data included a total of 9639 unique tags, representing approximately 94% of the raw data with numbers roughly evenly distributed among sexes (4740 and 4899 for female and male, respectively) (Table 1). Carapace lengths of tagged lobster ranged from 42 to 166 mm and averaged 93.1± 14.3 mm. The average size of females outside were 88.9 ±13.3 mm and males outside were 89.7 ± 12.6 mm, whereas females inside were 92.2 ±13.3 mm, and males inside were 98.1 ±15.1 mm. For this study, I used only lobster with recapture information where carapace lengths differed by at least 3 mm between successive captures, in order to separate growth from measurement error. Due to sparsity of the data, data were binned into 4-year intervals prior to analysis (Table 2). This binning was done to increase the robustness of the results because shorter time intervals would lead to problems with model conversion. Use of 4-year intervals provided a snapshot of what was happening inside and outside the MPA at a given time segment and not over the lobster's life. For example, a lobster tagged in 1997 that was not recaptured until 2004, would not provide information on everything that happened to the lobster across 7 years, but what differences were observed at the specific capture or recapture events. Data from multiple recaptures were excluded from the model to remove the need to account for individual growth behaviour within the model and meet the requirements of IID (independent and identically distributed) data. The model used in this study is appropriate for short time intervals with near linear growth increments.

Table 1: Total number of uniquely tagged male and female lobster in the Eastport Peninsula Lobster Management Area (1997-2012) from edited data. % breakdowns were rounded to the nearest 1%. The numbers of unique tags do not equal the total because lobster move between recorded boundaries and may have been counted in more than one category. These numbers include the unique tags captured inside and outside the MPA.

	Female	**Male**	**Total**
EPLMA	4740 (49%)	4899 (51%)	9639
Inside MPA	2685 (49%)	2804 (51%)	5489
Outside MPA	2177 (49%)	2229 (51%)	4406

Table 2: Number of unique tags recaptured for the first time for each of the 4-year bins. % breakdowns were rounded to the nearest 1%.

	Females	**Males**	**Number of Tags**
1997 - 2000	1391 (49%)	1417 (51%)	2808
2001 - 2004	926 (49%)	949 (51%)	1875
2005 - 2008	1186 (49%)	1250 (51%)	2436
2009 - 2012	1237 (49%)	1283 (51%)	2520

3.2.3 Growth Model

I estimated growth rates of American Lobster in the EPLMA using a generalized form of the von Bertalanffy growth model (see Bevacqua et al. 2010 for equation 1 to 5 derivations). The generalized form allowed estimates of growth parameters using time intervals, rather than relying on absolute ages.

$$\frac{dL}{dt} = a + bL \tag{1}$$

This approach estimates the difference of length (*dL*) over the time-span between the initial tagging and first recapture (*dt*) from its initial length (*L*) and the growth parameters *a* and *b*. The *a* and *b* parameters are the gradient and intercept parameters of the growth increment from the differential equation, which provide an opportunity to describe growth without including age data that cannot be collected in the tagging program. The von Bertalanffy growth model paired with individual change in size allows development of a relative size at age relationship without an absolute age (Chang et al. 2012). The equations 2 and 3:

$$L_\infty = \frac{a}{-b} \tag{2}$$

and

$$k = -b \tag{3}$$

provide the equivalency of the growth parameters used in the generalized form (*a* and *b)* where *k* is the Brody growth parameter and L_∞ is the asymptotic length when growth is zero (Bevacqua et al. 2010; Chang et al. 2012). Solving the differential equation (1) allows calculation of the estimated length at recapture (L_r) after Δt, introducing L_m, which is length at first measure (Equation 4, Bevacqua et al. 2010):

$$\widehat{L_r} = -\frac{a}{b} + \left(L_m + \frac{a}{b}\right) exp(b\Delta t) \tag{4}$$

Using the optimizer nlminb (Gray 1990) in R (R Core Team 2016), the cost function *J* was minimised in order to estimate *a* and *b* (Equation 5).

$$J(a,b) = \sum_{i} \frac{\left[ln(L_{i,r}) - ln\left(-\frac{a}{b} + \left(L_{m,i} + \frac{a}{b}\right)exp(b\Delta t_i)\right)\right]^2}{\sqrt{\Delta t_i}} \tag{5}$$

Given the sexual dimorphism of body size in lobster (females experience delayed growth when egg bearing), I modeled growth rates of females and males separately (Talbot and Helluy 1995). Additionally, I fitted models for four-year time blocks and inside and outside the MPA islands values published by Bevacqua et al. (2010). As with any nonlinear modelling procedure, starting parameter estimates for *a* and *b* were used, which are required for non-normal errors using iterative estimation. Sex-specific starting values were used with uncertainties in growth estimates determined by bootstrapping. I then used a nonparametric multi-sample bootstrap implemented in the R-package '*boot*' (Canty and Ripley 2015), running a total of 2000 bootstrapped samples for each group of year blocks, sex, and protection status. This method was chosen given the nature of the growth parameters for which distributions were unknown. Unknown parameter distribution prevented the use of generalized linear models and their extensions of generalized linear mixed effects models.

3.2.4 Regional variation in growth

Based on the growth model parameter estimates resulting from the Eastport tagging data, I extracted K and L_∞ values (Equations 1 and 2) for both male and female lobster. Growth comparisons with other regions across the American lobster range used the von Bertalanffy equation $L(t) = L_\infty\left(1 - e^{-K(t-t0)}\right)$ and parameter estimates from growth studies in Newfoundland and those published for the Bay of Fundy, Maine, and Rhode Island (Russell et al. 1978; Ennis 1980; Campbell 1983; Bergeron 2011). I then compared lobster ranging from ages 0 to 30 years and for sizes up to 300 mm.

3.3 RESULTS

3.3.1 Size distribution

On average, the Eastport CMR program reported 2.5 recaptures per unique tag, with an average recapture of 282 tags per year. From the data used in this study (1997-2012), 2644 unique tags were recaptured at least once after the initial tagging. The carapace length of lobster tagged in the EPLMA ranged from 42 mm to 166 mm, averaging 90.8 ± 13.4 mm for females and 94.9 ± 14.8 mm for males. Figure 3 shows a consistently higher mean carapace length for male and female lobster inside than outside the MPA each year.

Higher variances in length frequencies of male and female lobster also characterized individuals inside the MPA (Figures 4 and 5). In 2004, 7 years after the implementation of the closure, a notable shift occurred with a higher frequency of larger male and female lobster inside and outside the MPA, a pattern consistent with the findings from Janes (2009) and Collins (2010) (Figures 4 and 5).

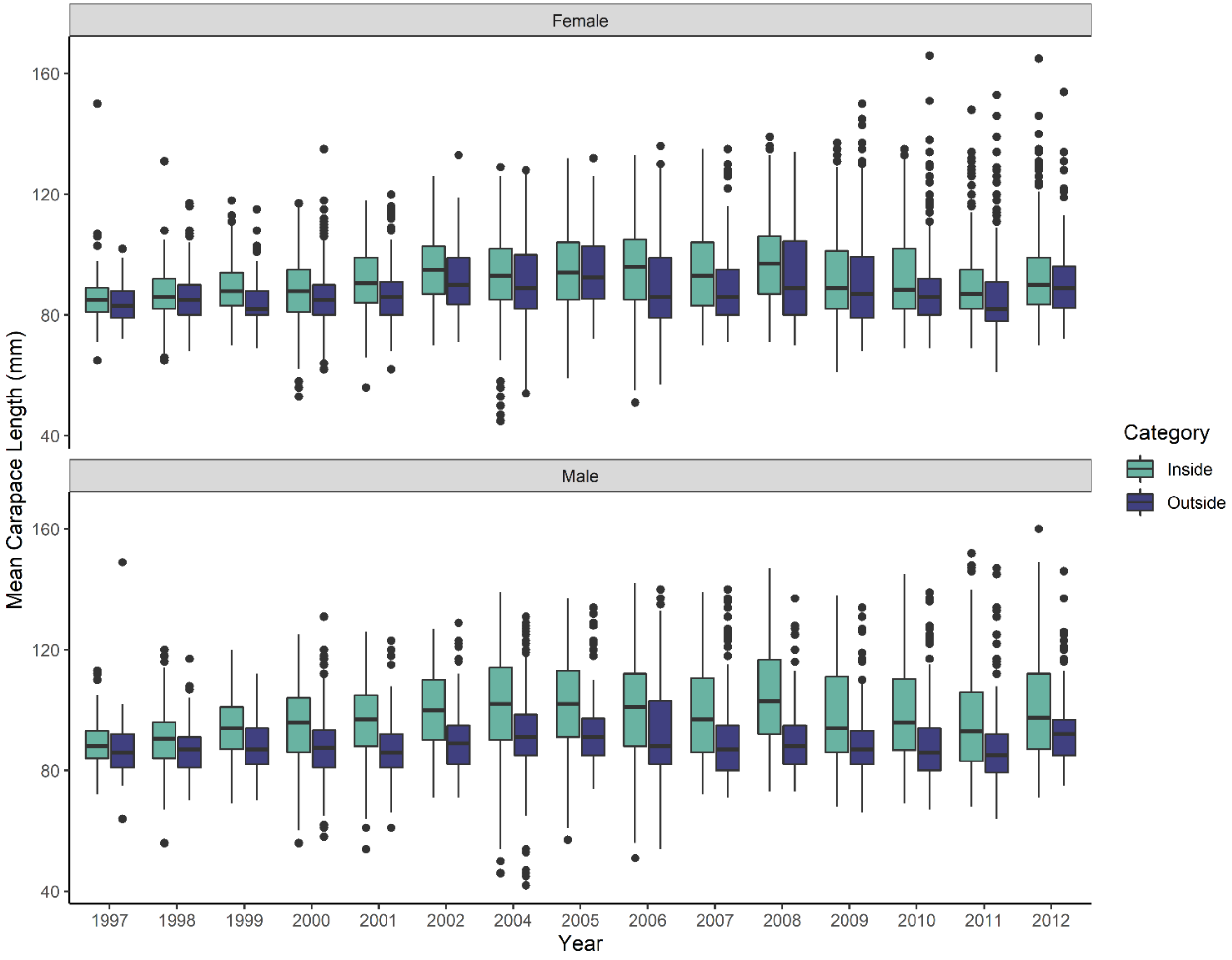

Figure 3: Mean carapace length of female and male lobster inside and outside the Eastport MPA from 1997 to 2012.

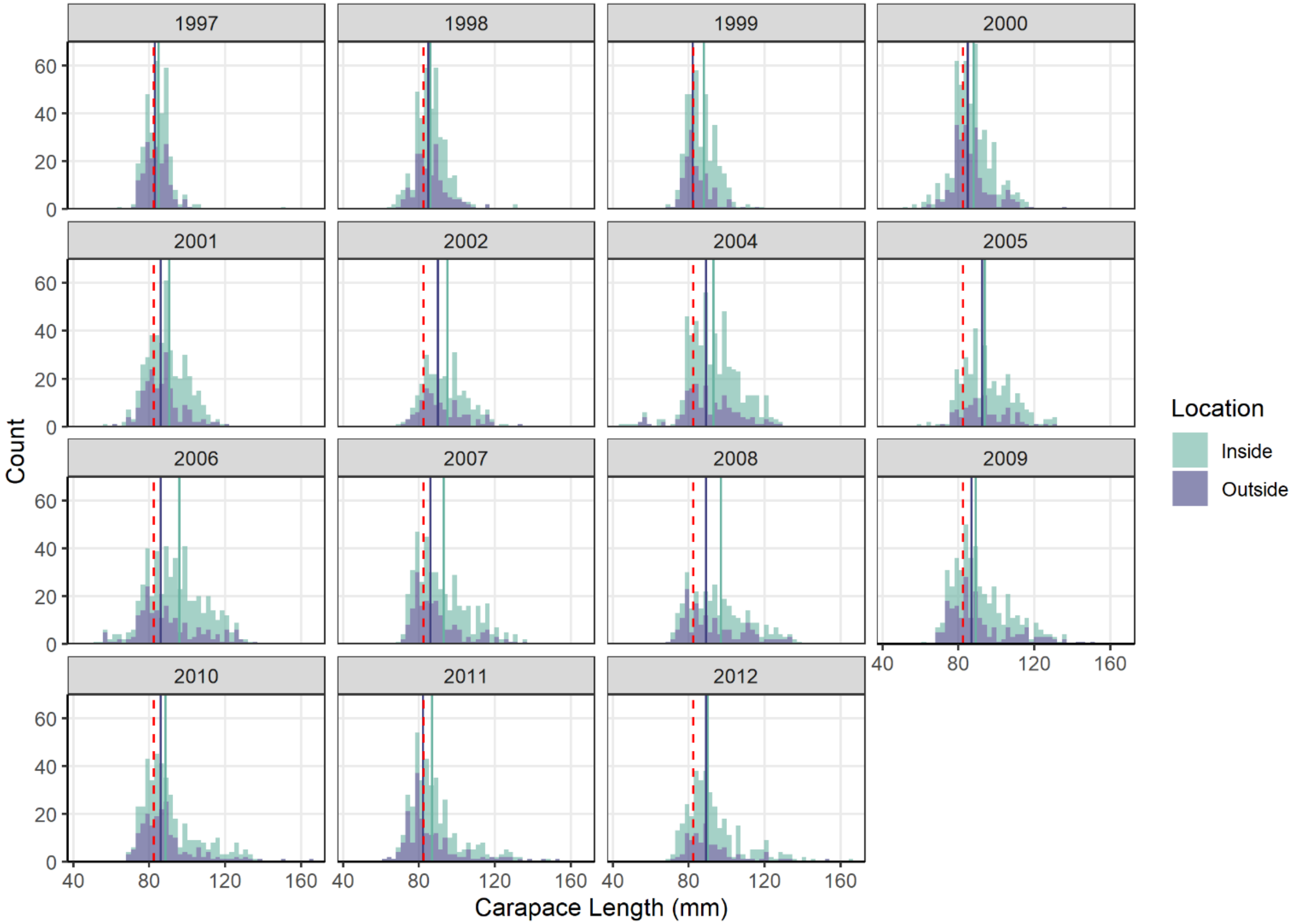

Figure 4: Frequency distribution of female carapace lengths inside and outside the MPA. Green vertical line is median carapace of female lobster inside, purple vertical line is median carapace of female lobster outside and red dotted vertical line is the 82.5mm minimum legal size.

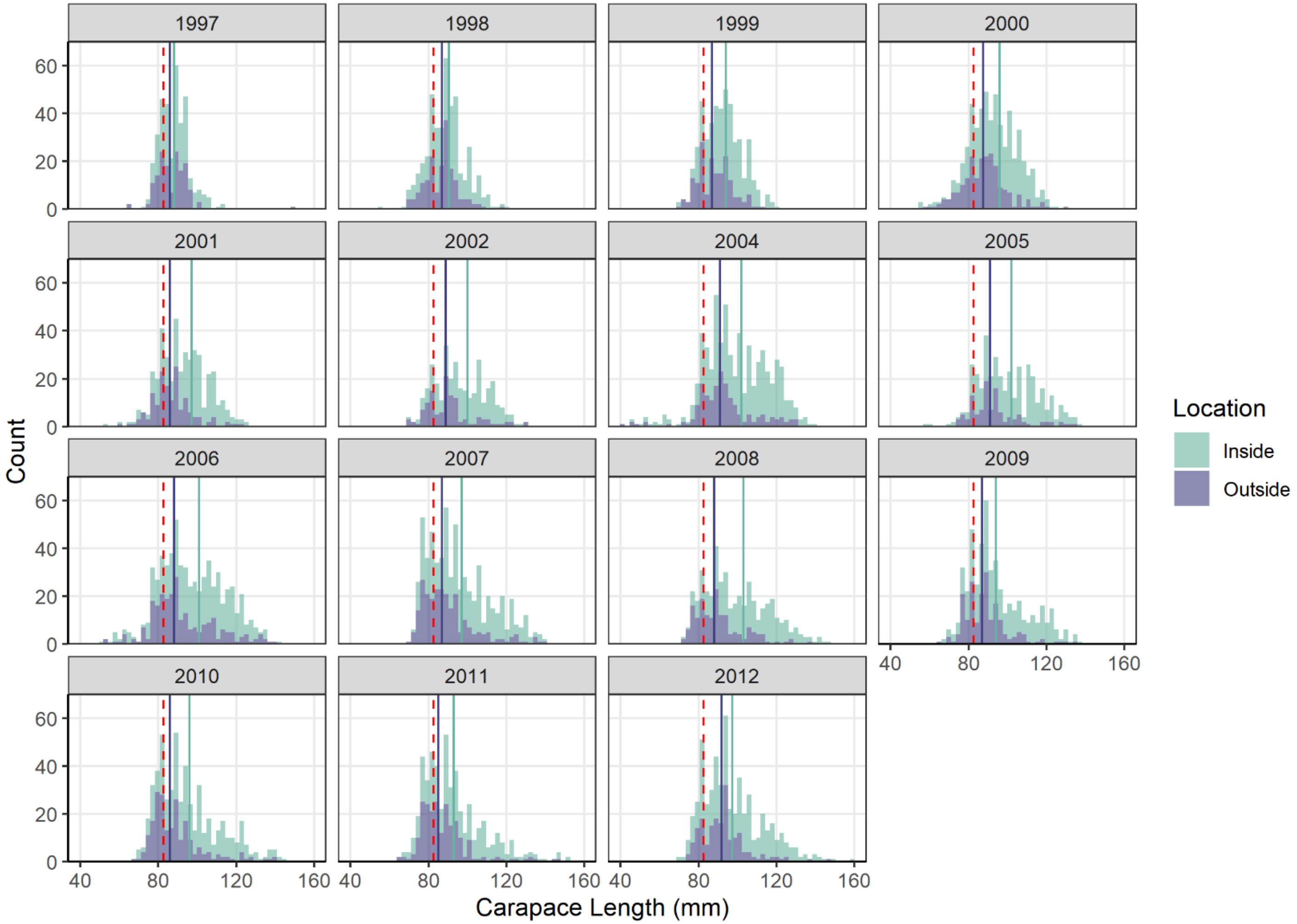

Figure 5: Frequency distribution of male carapace lengths inside and outside the MPA. Green vertical line is median carapace of male lobster inside, purple vertical line is median carapace of male lobster outside and red dotted vertical line is the 82.5mm minimum legal size.

3.3.2 Growth Rate

Growth rates of male and female lobster were estimated based on the von Bertalanffy growth model for the entire EPLMA and shown for both sexes captured inside or outside of the MPA. The growth parameters *a* (gradient of the growth increment) and *b* (the intercept of the growth increment) were calculated from a non-parametric bootstrap distribution and are shown with the upper and lower 95% confidence intervals of the median point estimate (Figure 6). Both growth parameters (*a* and *b*) show no difference between lobster inside and outside the MPA over the majority of time intervals (Figure 6), indicating that the asymptotic length ($L_{inf} = a/-b$) did not vary over the conditions observed. The growth parameter estimates for males do not show statistically significant differences in the 4-year interval (2009-2012) (Figure 6) as inferred from overlapping 95% confidence intervals. Growth parameter estimates in Figure 6 for females showed consistently similar results inside and outside the MPA across all 4-year intervals. There were insufficient data to make year by year comparisons, and 4-year intervals represented the smallest time frame to obtain robust parameter estimates. The male lobster sampled from within the MPA from 1997-2008 generally exhibited larger annual growth and larger L_{inf} (Figure 7) as well as greater uncertainty around the parameter point estimates, however, the comparisons were not statistically significant. Figure 7 shows the von Bertanlanffy curve based on the model outputs of *a* and *b* converted to *k* and *Linf*, providing an overall estimation of growth for male and female lobster inside and outside the MPA. Although there appear to be differences in the growth parameters in Figure 6, they do not translate into actual growth (as shown in Figure 7), *a* and *b* are interacting growth parameters that together dictate the shape of the growth curve.

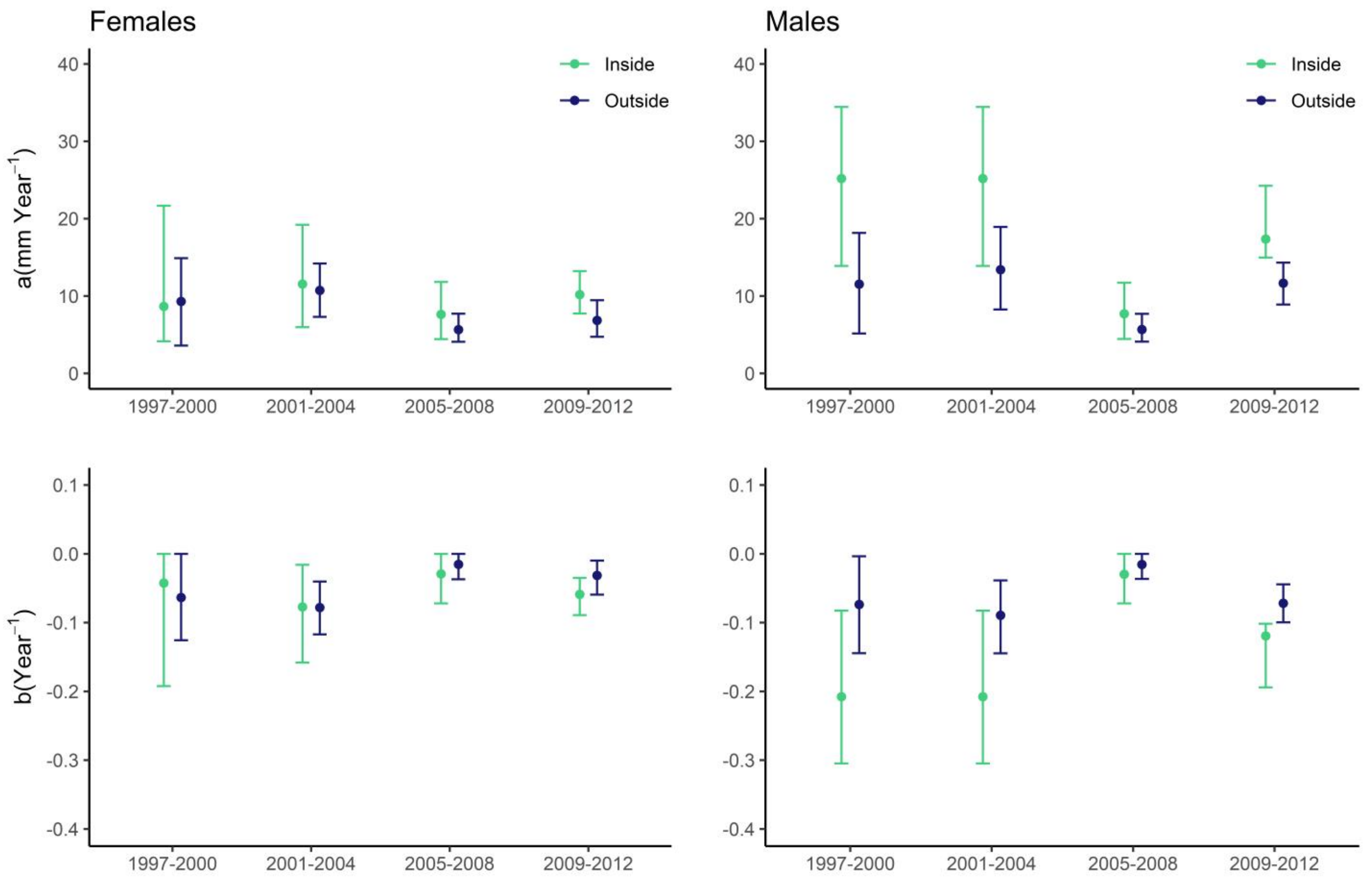

Figure 6: Male and female growth rates from 1997 to 2012 inside and outside the Eastport MPA. Mean growth estimates with 95% confidence intervals.

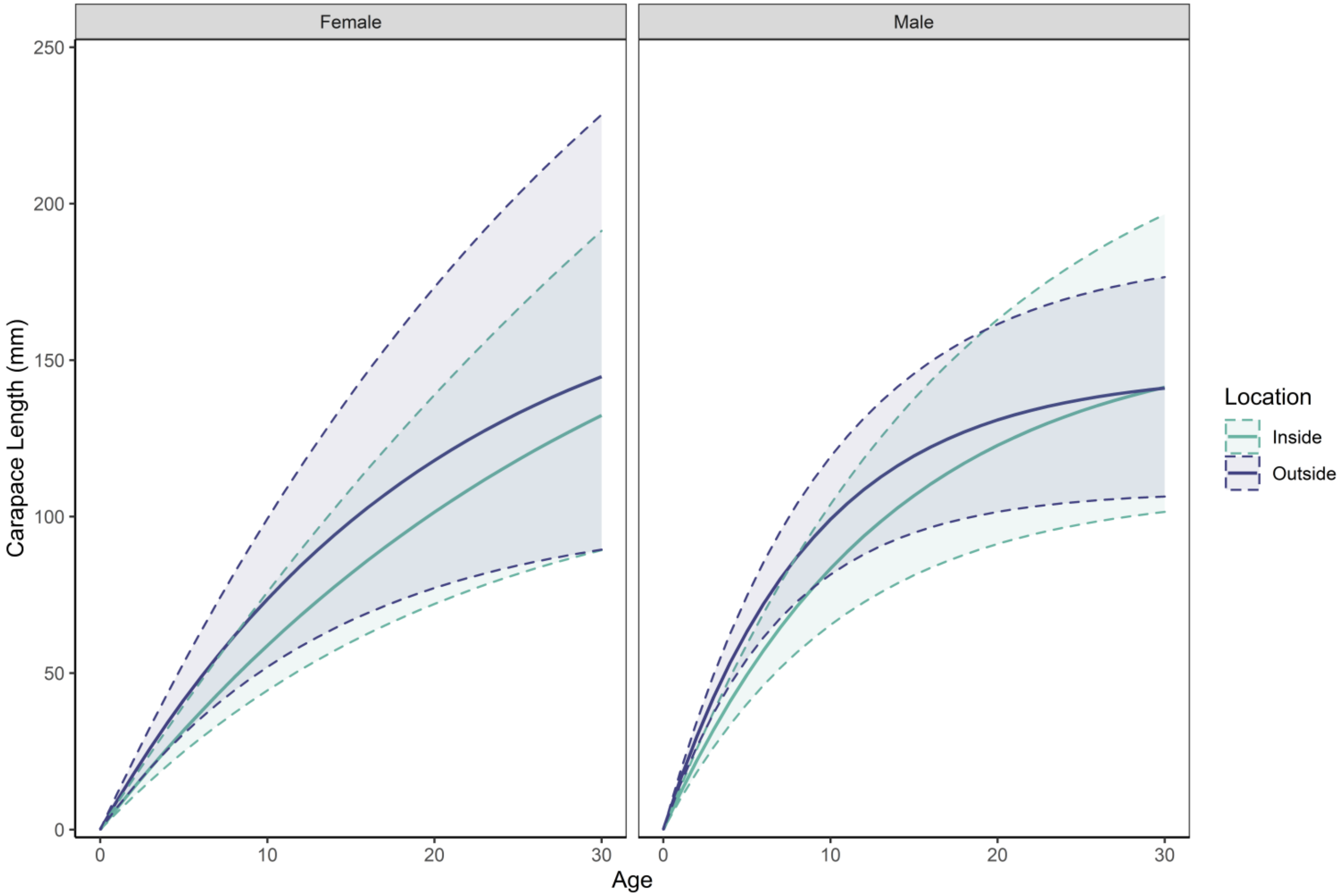

Figure 7: Von Bertalanffy growth curves for female and male lobster inside (green line) and outside (purple line) the Eastport MPA estimated over 30 years of age with 95% confidence intervals shown in corresponding colour ribbons.

3.3.3 Regional variation in growth

The growth rate observed in the EPLMA closely resembled that observed by Ennis (1980) for Newfoundland lobster (Figure 8). Both male and female lobster in the Eastport area showed a slower rate of growth, with a lower asymptotic length than populations from other regions. Males typically grew faster than females, as shown by a generally steeper curve. Among the regions compared, lobster in the EPLMA were the slowest to reach legal size (Figure 8). By comparing age at a carapace length of 85 mm (just over or at legal size for all regions) the Eastport lobster took on average 6.2 ± 0.9 years longer to reach 85 mm carapace length for females and 2.1± 1.5 years longer for males than lobster from the other regions (Figure 8).

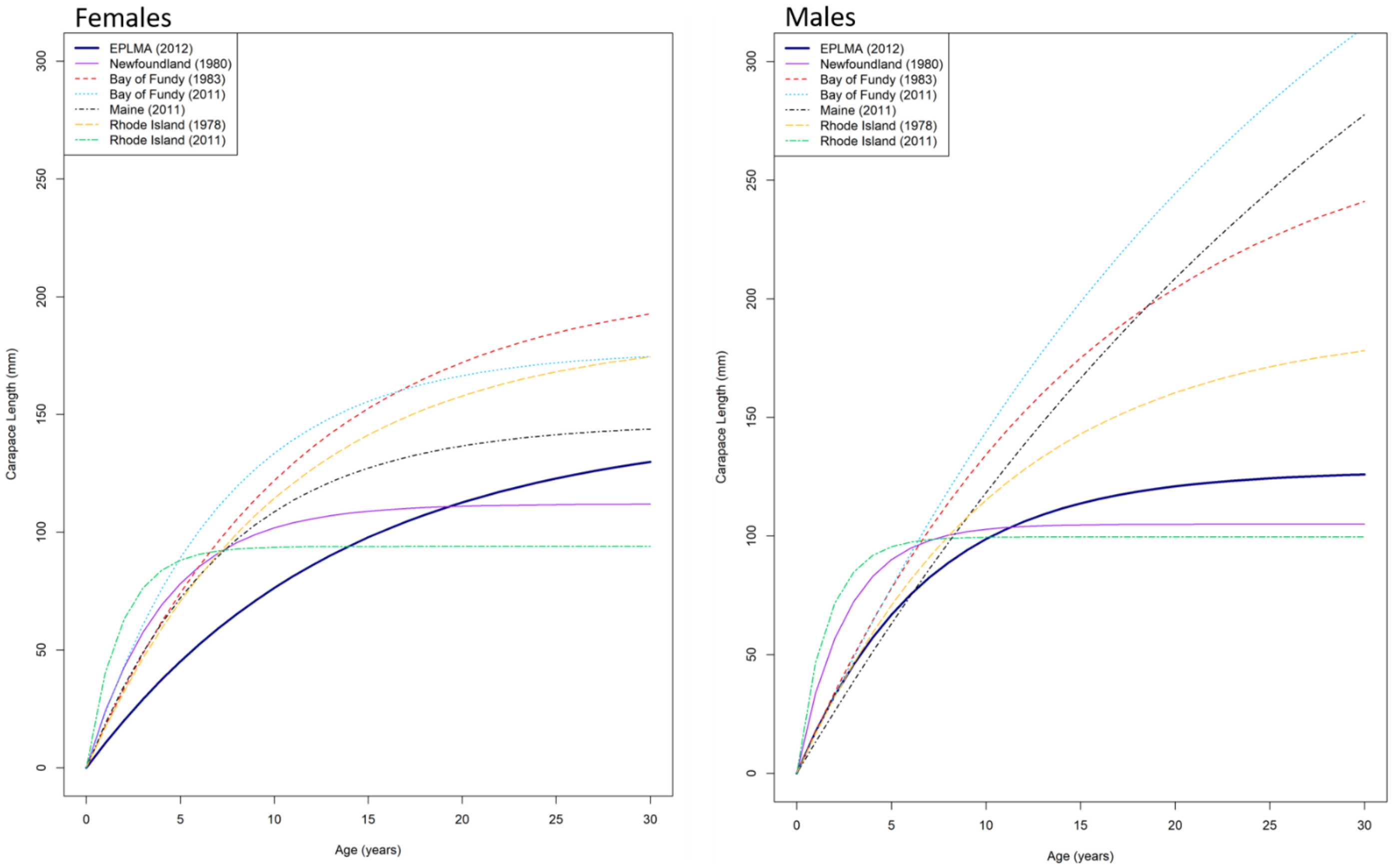

Figure 8: Comparison of growth curves for female and male American lobster across their geographic range. Parameter estimates of growth encompass a variety of studies using different methods for parameter estimates. Newfoundland shown in purple (Ennis 1980), Bay of Fundy shown in red (Campbell 1983), Bay of Fundy shown in light blue (Bergeron 2011), Maine shown in black (Bergeron 2011), Rhode Island shown in yellow (Russell et al. 1978) and Rhode Island in green (Bergeron 2011).

3.4 DISCUSSION

Using a 15-year time series of tagging data from the Eastport Peninsula I quantified the size frequencies and growth trajectories for male and female lobster, inside and outside the Eastport MPA, documenting change over time. Length frequency histograms showed generally more variability in lobster size, and more numerous larger lobster inside the MPA than in the surrounding waters. This difference likely results from the protection of larger lobster from the fishery inside the MPA boundaries (average size outside was 88.9 ±13.3 mm and 89.7 ± 12.6 mm and inside 92.2 ±13.3 mm and 98.1 ±15.1 mm, for females and males respectively). Three types of traps have been used for sampling: commercial, small modified, and large modified. Without information on catch effort in each of the sampling locations it is difficult to distinguish what role the changes over time and variability in sampling methods played in the results. Following the inception of the fishery closure (1997) female lobster inside and outside the MPA have exhibited a relatively steady growth rate over time whereas male lobster have demonstrated a more variable growth rate with lower estimates from 2005-2012 from previously higher rates. I detected no obvious difference between growth rates inside and outside the MPA. The negative correlation between *a* and *b* complicates separation of decreased growth from an increase in the asymptotic average length. Overall growth curves of female and male lobster show steeper growth outside than compared to lobster inside the MPA.

Lobster growth in the EPLMA

I expected a difference in growth between adult male and female lobster because of the high energetic cost of egg production and because egg bearing females cannot molt while carrying a clutch. The number of times a female produces a clutch also impacts growth patterns (Abrams and Rowe 1996; Chang et al. 2012). Additionally, female lobster migrate between the warm inshore and cool offshore waters to optimize egg development by finding ideal water temperature, and temperature significantly impacts growth (McMahan et al. 2016). Therefore, limited change in female growth over the 16 years of data is not surprising. Females receive protection not only in the MPA but in the fished areas when berried or notched experiencing substantially less fishing pressure than males as a result of these additional protections. The declining or steady growth rate in the area may also be attributed to the MPA, in that the prevention of fishing in the area would mean fewer baited traps with readily available food (Grabowski et al. 2009). Previous studies note more numerous larger males inside the closed area and an upward trend in mean carapace lengths for both sexes (Janes 2009; Lewis et al. 2017), meaning larger lobster potentially displaced smaller, faster-growing lobster from the MPA.

Variations in lobster growth regionally

Slower growth rates characterize Eastport lobster compared to lobster populations across the species range; the Eastport population was the smallest at 10 years and the slowest to reach commercial size, with females and males taking 6 and 2 years longer on average to reach 85 mm than lobster from populations across the species range. Variations between the curves may be attributed to differences in methods, sample sizes and the size ranges captured in each region. Plotting growth curves of American lobster populations throughout their range allowed me to compare variation in growth rate and differences between males and females. Variation between curves is expected given the impact of temperature (Aiken and Waddy 1986) (and thus latitude) on lobster growth rate (Raper and Schneider 2013). Lower temperatures typical of higher latitudes slow growth and delay maturation, whereas warmer waters promote faster growth and maturity at a smaller size (Templemen 1936; Waddy and Aiken 1995), as is typical in most ectothermic organisms. Understanding this variation in growth throughout a species' geographic range helps in managing fishing stocks, given the central importance of growth rate in determining minimum legal size (usually based on the size of sexual maturity), maximum yields and egg-per-recruit models, lifespan, and in identifying cohorts (Davis and Dodrill 1989; Comeau and Savoie 2001; Chang et al. 2012; Raper and Schneider 2013). For example, previous studies demonstrate temperature-dependent age-at-recruitment, where the timespan for recruitment scales negatively with temperature (Aiken and Waddy 1986; Campbell et al. 1991; FRCC 1995; Grabowski et al. 2009). Variability in growth rate may reflect the effect of temperature on metabolism (Grabowski et al. 2009) whereby reduced metabolic rates associated with colder temperatures reduce growth. Furthermore, increases in population density can reduce food availability, which may, in turn, limit growth as show in other lobster species populations (Tuck et al. 1997; Haley et al. 2011). Population density estimates for the Eastport MPA have varied through time and the protected area has been shown to support increases in lobster densities (Lewis et al. 2017). Increases in lobster density and a potential reduction of resource availability for lobster in the MPA could have contributed to a decrease in growth.

Lobsters experience stepwise growth as they molt, regularly shedding the calcified structures that might otherwise be used in determining age (Chang et al. 2012). This growth pattern complicates quantification of age and growth rate. Growth rate in American lobster (*Homarus americanus),* a relatively slow growing, long-lived marine species, increases with increasing temperature because they molt more frequently, with lower mean growth increments, reach maturity at a smaller size and age and, in turn, recruit more quickly (FRCC 1995; LeBris et al. 2017). Growth for many marine species is a highly plastic trait, influenced by temperature, habitat and resource availability, population status, and fishing pressure (FRCC 1995; Sanchez Lizaso et al. 2000; Raper and Schneider 2013). Monitoring growth within an unexploited area provides a unique opportunity to develop a baseline for growth rates under (near) natural conditions compared to the exploited portion of the population (Davis and Dodrill 1989).

Outcomes from the Mark Recapture program

Previous research on lobster in the Eastport MPA analyzed length frequencies and changes in average carapace length over time, but did not use the mark-recapture data to quantify growth rate of lobster in a protected area. The Eastport lobster population increased in mean size for male and female lobster, inside and outside the MPA over time (Janes 2009; Collins 2010; Lewis et al. 2017). For this study, using growth to monitor the contribution of the MPA to the preservation of the Eastport lobster population added challenges. My study utilized the data from a CMR program established in 1997 when the area was first closed to fishing. The area was later designated as an MPA (2005), but no relevant data prior to the establishment of the closure exists, complicating efforts to evaluate the efficacy of MPA implementation as a reserve for local lobster. A study on a lobster population in Bonavista Bay found the average movement of tagged lobster for 11 to 13 months to be 0.4 km with a maximum range of 1 km (Ennis et al. 1989). The Eastport MPA collectively covers 2.1 km^2, which complicates efforts to infer what impact the MPA has had on the population given that lobster could, and likely do, move out of the protected area. The design process of MPAs typically considers size as a key criterion. The protected area should encapsulate movement and life history phases of the target species in order to reduce the probability of the target species leaving the area of protection (Roberts et al. 2003; Green et al. 2014).

Contributions of an MPA to growth

Previous studies demonstrate that marine protected areas can benefit slow-growing benthic species such as lobster. When protected by the no-take Te Tapuwae o Rongokako Marine Reserve in New Zealand, spiny lobster (*Jasus edwardsii)* males grew at faster rates than those in the surrounding area, with a larger molt increment inside the reserve than sub-legal sized males outside the reserve (Freeman et al. 2012). Another species of spiny lobster (*Palinurus argus*), in Florida, responded positively to MPA protection with growth rates almost twice those in the surrounding fished area, a difference that reflected the optimal habitat located within the MPA (Davis and Dodrill 1989). In contrast I found decreased growth rate of lobster in the Eastport MPA and larger EPLMA over the duration of the mark-recapture period analyzed here. This observation may link to available habitat, which regulates both the abundance and size of lobster inside versus outside the MPA. Habitat classifications for the MPA and surrounding area reported a preponderance of shallow rocky substrate in the MPA, which is optimal habitat for juvenile lobster (Novaczek et al. 2017). However, adult lobster typically prefer rocky substrates with boulders that provide shelter (Steneck 2006; Inzce et al. 2010), suggesting sub-optimal habitat within the MPA for adults. Larger lobster may leave or avoid the MPA because they require more shelter from boulder habitat, contributing to the lack of larger faster growing lobster in the MPA.

MPA size may also limit the relative benefit of protection for the local lobster population. Model simulations developed for Caribbean spiny lobster (*Panulirus argus*) in Exuma Sound, Bahamas, suggest that a single large reserve would enhance larval production and growth rate more than an equivalent size of reserves divided into multiple smaller pieces (Stockhausen and Lipcius 2001). American lobster may require 8 years to reach commercial size (Gendron and Sainte-Marie 2006), likely longer in the colder waters of Newfoundland. Given that the area closed to fishing in 1997, insufficient time may have passed to detect any contribution from the MPA to lobster growth rates given that data for this project likely covers only one generation for local lobster. In lieu of information on absolute age of lobster, I used a generalized version of the von Bertalanffy growth model to estimate the growth rate of Eastport lobster (Bevacqua et al. 2010). The extensive mark-recapture program in the Eastport MPA provides a useful time series for Newfoundland lobster science while demonstrating the importance of data collection prior to fisheries management and conservation efforts such as an MPA. It is difficult to say how the MPA contributes to the local lobster population; my results suggest that it may contribute little or nothing to local lobster populations, alternatively, we may lack sufficient information to draw definitive conclusions. The mark-recapture program nonetheless provides a long and consistent time series of detailed data on individual size, sex ratio, and length frequency that define the local lobster population. Information from this monitoring program can help to advise Newfoundland lobster stock assessments that require growth information.

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CHAPTER 4: General Conclusions

Governments worldwide have adopted marine protected areas (MPAs) as a biodiversity conservation tool, increasing MPA global coverage towards targets identified in international agreements (*i.e.*, conserving 10% of coastal and marine areas by 2020 through protected areas or other effective conservation measures (Aichi Target 11, 2019)). Generally, managers have developed MPAs as a tool to meet multiple conservation objectives such as protection of areas of special interest, unique habitats, at risk or endangered species, or enhancing recovery of highly exploited commercial species. Despite relatively well-developed conservation merits of MPAs (Gill et al. 2017), implementation often brings the challenge of balancing existing human activities (*i.e.*, fishing grounds) when considering MPA design (*e.g.,* location, size, and zoning required to ensure MPAs can meet their conservation objectives). Managers must establish long-term monitoring programs after MPA implementation in order to evaluate objectively the success of the management intervention (*i.e.*, the design of the MPA) relative to its conservation goals. This information often represents an important tool for securing support from stakeholders.

Establishment of the Eastport MPA

The Eastport Marine Protected Area was initially established as a community-led fisheries closure in 1997. The primary goal was to increase egg production by limiting fishing, based on advice from the Fisheries Resource Conservation Council (FRCC 1995; Collins and Lien 2002). This relatively small closure of just 2.1 km^2, encompasses 0.525% of the Eastport Lobster Management Area (400 km^2) and <1% of the regional Lobster Fishing Area (LFA 5). Observations of the movement scale of adult American lobster range from very localized (>1 km) to long-distance migrations exceeding 100 km (Cooper and Uzmann 1971;

Campbell and Stasko 1984; den Heyer et al. 2009). In Newfoundland, observations of lobster movement indicate more localized ecological ambits than reported elsewhere (Ennis 2011); the Eastport MPA may therefore provide some degree of protection for resident adults, despite its small size, in contrast to lower latitude populations where movement scales would likely mismatch the MPA's spatial extent.

In consultation with scientists, the Eastport Peninsula Lobster Protection Committee identified the area around Duck and Round Island as critical habitat for lobster (Collins and Lien 2002). In 2005, the fisheries closures received official status as an Oceans Act MPA (Minister of Justice 2005). Though data was not collected prior to the establishment of the closure, an annual mark-recapture program within the EPLMA has been ongoing since 1997 in the fall of each year. These factors contribute to a focus on the Eastport area for lobster research in Newfoundland, with annual monitoring programs recording data on population structure, size structure, density, reproductive potential, sex ratio, and movement (Janes 2009 Collins 2010; Lewis et al. 2017). A primary objective of the monitoring program was to collect information that can help evaluate the productivity of the MPA and surrounding areas. In order to build on this objective, my thesis primarily focused on determining a local measure of fecundity, egg production, and growth rate for the MPA and surrounding EPLMA, and comparing these characteristics to other populations throughout the species range.

Summary of Work

To test for the presence of spillover through a size or fecundity gradient from the boundary of the MPA into the EPLMA, I measured fecundity of berried females in the field during the commercial fishery. I found no significant trend in fecundity or female carapace size along a gradient from within the MPA to the MPA boundary. Modelling changes in egg production over time inside and outside the MPA showed an increased in estimates of production, meaning the MPA could increase local reproductive value. Using measured size fecundity relationships and those published in the primary literature, I found higher fecundity at commercial size in the Eastport lobster population (throughout EPLMA) than other populations in the species range. Tagging data from the mark-recapture program collected from 1997 to 2012 revealed higher variance in length frequencies for male and female lobster inside the MPA than outside the MPA. Lobster inside and outside the MPA experienced a slightly decreased growth rate since the inception of the fisheries closure in 1997. Growth rate was higher for males than females both inside and outside of the MPA, and plotting the overall von Bertalanffy growth for female and male lobster over an estimated 30 years showed steeper growth for lobster outside than inside the MPA. Plotting growth curves for lobster across their geographic range showed a slower growth rate for the Eastport lobster population, which was the slowest of those examined to reach legal size.

Despite some ambiguity regarding whether the MPA achieved its conservation objective of enhancing local lobster fecundity and growth, the monitoring program nonetheless provides valuable regional data useful for stock assessments and fisheries management. As an indicator for stock assessments reproductive potential requires information on fecundity at size, abundance of females at size, and size of maturity to estimate the potential of eggs produced within a stock (Cook et al. 2017). Stock assessments use proportion of new recruits to indicate the fisheries reliance on new recruits to the stock, and this indicator requires information on growth rates and length frequencies in the population (Cook et al. 2020). The MPA has existed as a fishing closure for over 20 years and was established at the same time as other management measures (increased in minimum legal size, and v-notching) that can influence demographic changes to local lobster populations. This coincidence in timing complicates the interpretation of the potential impacts of each management decision. Additional data would be helpful in looking at phenotypical changes in growth and fecundity to be certain about the effectiveness of the Eastport MPA. Clawed lobsters can demonstrate phenotypic changes in their growth as adults, size of maturity, fecundity, as well as enhanced growth and development in early life stages, as a response to environmental factors - particularly increases in temperature (Pollock 1995; Pollock 1997; Harrington et al. 2019). The additional data would be particularly valuable given that the MPA is relatively young, especially compared to the generation time of lobster.

The egg production estimates from my study suggest increased egg production in the area, however, quantifying whether egg production translates to benthic recruitment may be impossible (Stanley et al. 2018). Egg-per-recruit models, which have been used to determine reference points for lobster fisheries management, require quantifying local fecundity and growth for a population (Comeau and Savoie 2001). The Eastport MPA also offers a good example of community-led conservation, and the ongoing standardized, fisheries-independent monitoring program provides valuable time series data not collected anywhere else in the province. Efforts to quantify tangible ecological benefits of the Eastport MPA also illustrates the importance of collecting baseline data prior to closing an area in order to compare pre- and post-closure growth rates and size structure.

Future Work on the Eastport MPA

Future efforts to monitor the MPA should include spatial data that addresses finer-scale (100s of m) movements in and out of the MPA to understand whether lobster actually receive protection. Recording effort data during the tagging program by noting traps (commercial, small modified, and large modified) used in each sampling location (Figure 1: Chapter 3) and the number of lobster per trap (catch per unit effort) would be a helpful additional to clarify differences in the population inside and outside the MPA. Including collection of temperature data as part of the MPA monitoring program would be informative, given that temperature strongly influences growth, egg development and spawning of American lobster. Temperature information could help explain trends in growth rate, such as the decreased growth inferred from the tagging program. To characterize the size-fecundity relationship for the area more effectively, I suggest the use of modified traps to capture and tag pre-recruit and jumbo (typically >120 mm) lobster that existing monitoring/tagging program data overlook.

Previous research on the Eastport MPA primarily focused on monitoring its impact on local lobster by examining changes in population size and structure overtime, reproductive potential, movement and catch per unit effort (Janes 2009; DFO 2013; DFO 2014; Lewis et al. 2017). A recurring question with respect to the Eastport MPA is the effectiveness of its size (2.1 km^2) and design (perimeter of two islands in a 400 km^2 management area). Research moving forward could model the possibility of expanding the size of the MPA (Duck and Round Islands), or the addition of other locations towards a network design to determine how to address better the conservation objectives of the MPA, and how the closure could better support the fishing communities in addition to local marine populations.

In closing, my analyses did not provide clear evidence that the Eastport MPA achieved the conservation objectives identified when the MPA was established. The absence of a “smoking gun” may reflect insufficient data, or it may suggest that the small size of the MPA relative to lobster movement may either negate any real benefits, or that it may obscure detection of any potential benefit. Nonetheless, the conservation ethic that the MPA has clearly helped foster among local fishers offers a tangible step in the right direction that could provide ecological benefits that may indirectly support the broader conservation objectives for the Eastport MPA.

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