Modelling fishing effort displacement in the Southern Gulf of St Lawrence snow crab (*Chionoecetes opilio)* fishery: quantifying management measures for North Atlantic right whale (*Eubalaena glacialis)* entanglement prevention

By

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ABSTRACT

Anthropogenic mortality is the leading factor inhibiting the recovery of the endangered North Atlantic right whale (NARW), in which 85% of human-induced deaths are caused by entanglement in commercial fishing gear. In 2017, a large number of NARW entanglements and deaths occurred in the Gulf of St Lawrence, many of which were attributed to the snow crab fishery. This led to the establishment of new management measures, including spatio-temporal fishery closures in the form of static and dynamic exclusion zones that encompassed 90% of the 2017 NARW sightings. These measures raised concerns related to the costs to the fishery and effectiveness of entanglement prevention. Using fishing data from 2005 through 2012, a model was built that predicted weekly fishing effort displacement caused by these closures, the approximated socio-economic costs of movement, and relative change in co-occurrence, or risk, of a NARW coming into contact with fishing gear. The model examined four alternative closure arrangements to evaluate NARW protection efficacy versus costs to the fishery of different management strategies. Results show that lost fishing opportunity was minimal, and estimated costs were highest and most variable in the current strategy, and lowest and most consistent in a strictly dynamic management regime. While displaced effort resulted in a fishing-the-line scenario, all strategies were successful at reducing the threat of entanglement. Subsequently, this study quantifies and examines the trade-offs of spatio-temporal fishery closures for species-at-risk protection, while providing managers with an adaptive management tool in the form of the displacement model.

Keywords: spatial closures, fisheries impacts, entanglement, North Atlantic right whale, fishing effort displacement; conservation

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LIST OF ABBREVIATIONS

ATBA	Area to be Avoided
CFA	Crab fishing area
COSEWIC	Committee on the Status of Endangered Wildlife
CPUE	Catch per unit effort
DFO	Fisheries and Oceans Canada
DMA	Dynamic Management Area
EBM	Ecosystem based management
ESA	Endangered Species Act
GMB	Grand Manan Basin
IFD	Ideal free distribution
IMP	Integrated Management Plan
IMO	International Maritime Organization
ITQ	Individual transferable quota
IUCN	International Union for Conservation of Nature
MEOPAR	Marine Environmental Observation Prediction and Response Network
MMPA	Marine Mammal Protection Act
NARW	North Atlantic right whale
NB	New Brunswick
NFL	Newfoundland and Labrador
NOAA	National Oceanic and Atmospheric Administration
NS	Nova Scotia
PBR	Potential Biological Removal
PEI	Prince Edward Island
QC	Quebec
RB	Roseway Basin
SARA	Species at Risk Act
sGSL	Southern Gulf of St Lawrence
TAC	Total allowable catch
UME	Unusual mortality event
US	United States
VMS	Vessel Monitoring System
VPUE	Value per unit effort
WGS	World Geodetic System
WHaLE	Whales, Habitat and Listening Experiment

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1. CHAPTER ONE: INTRODUCTION

1.1. North Atlantic Right Whales

The North Atlantic right whale (NARW), *Eubalaena glacialis*, is a large baleen whale that can grow up to 18 meters in length and weigh up to 70 tonnes (DFO, 2018c; NOAA, n.d.-a). NARWs are easily recognized by their large heads, robust black bodies, lack of dorsal fin, broad, deeply notched flukes, and rough patches of white skin, known as callosities, around the top of the head, mouth and eyes (Figure 1.1; DFO, 2018c; Baumgartner, 2002). Historically abundant throughout the Atlantic Ocean, NARWs were heavily hunted by whalers, as they were considered the “right” whale to hunt due to their size and thick blubber, which provided large quantities of meat and oil, in which the latter kept their carcass floating after death for easy retrieval (Kraus et al., 2005; Szabo, 2018). After nearly hunting them to extinction, they were globally protected from commercial whaling in 1935, however, they are rarely seen in their historic Eastern Atlantic habitat, and are almost solely found in the Western Atlantic Ocean (Kraus et al., 2005; Cooke, 2018; COSEWIC, 2013). A highly migratory species, most pregnant females give birth over the winter months in the coastal waters off of Florida and Georgia, before travelling along the Eastern United States (US) to spend the summer months with much of the rest of the population feeding along the Northeastern US and in the Canadian Maritimes. Their primary feeding grounds have been identified as the Gulf of Maine, Bay of Fundy, Scotian Shelf, and most recently, the Gulf of St Lawrence (Figure 1.2; Cooke, 2018; COSEWIC, 2017).

Figure 1.1 Illustration of a NARW (Scott Landry, Provincetown Centre for Coastal Studies).

Despite their protection from whaling, the population has struggled to recover and NARWs remain one of the most endangered whales on the planet (Kraus et al., 2005; Pettis et al., 2017).

With an estimated population of approximately 411 individuals remaining, in which only 100 are estimated to be breeding females, NARWs are listed as endangered on the International Union for Conservation of Nature (IUCN) red list of threatened species (Pace et al., 2017; Cooke, 2018; NOAA, 2018b; Greenhalgh, 2018). NARWs are federally protected in the US under both the *Endangered Species Act* (ESA) and *Marine Mammal Protection Act* (MMPA), while being listed as Endangered under *ESA* and depleted under *MMPA*; in Canada they are federally protected and listed as Endangered under the *Species at Risk Act* (SARA) (NOAA, n.d.-a; SARA, 2018). They are also listed as Endangered in Canada by the Committee on the Status of Endangered Wildlife (COSEWIC), as well as additionally protected by the Marine Mammal Regulations under the *Fisheries Act*, which is managed by the department of Fisheries and Oceans Canada (DFO; COSEWIC, 2013; SARA 2018).

Prior to 2010, NARWs saw an approximate annual 2.8% increase in growth until 2010, when calving rates dropped by 40% (Kraus et al., 2016). The cause of this sudden decrease in population growth rate remains unknown, but is thought to be contributed by factors such as inbreeding, habitat degradation, food sources and competition, pollution, and anthropogenic stressors (Baumgartner & Mate, 2005). In addition to the drop in calving rates, increasing numbers of NARWs are being killed by human activities, identifying anthropogenic mortality as a major factor limiting the population's recovery in terms of overall population survival (Knowlton & Kraus, 2001; Kraus et al., 2016; Corkeron et al., 2018). Specifically, NARWs are highly susceptible to ship strike and entanglement in fishing gear, as their habitat is heavily used by the shipping and fishing industries (Kraus et al., 2005; 2016). Estimates from 2010-2014 show that an average of 5.66 NARWs are seriously injured or die from human-induced events annually; ship strikes were determined to contribute to 1.01 deaths, while the remaining 4.65 were associated with entanglement events (NOAA, 2018b). Under *MMPA*, the potential biological removal (PBR), the maximum number of individuals that can be removed from the population due to human-causes without negatively affecting population recovery, is calculated as a means to assess the stock status of a marine mammal population for management purposes; for NARWs, the current PBR is 0.90 (Ballance & Moore, 2014; NOAA, 2018b). Since 2010, 85% of all recorded, human-induced NARW deaths are attributed to entanglement in fishing gear, compared to 35% from 1970-2009 (Kraus et al. 2016). Additionally, further research has shown that 82.9% of all photo-identified

NARWs have been entangled at least once in their lifetime, indicating the severe pressure commercial fisheries put on this already struggling population (Knowlton et al., 2012).

In order to mitigate some of these anthropogenic impacts to NARWs in Canadian waters, Grand Manan Basin (GMB) in the Bay of Fundy, and Roseway Basin (RB) off of Southwestern Nova Scotia (NS) were identified as important habitat and designated as "conservation areas" in 1993 (Figure 1.2; COSEWIC, 2003). However, neither of these areas had any legislative framework to manage human activity until 2007, when GMB was designated as critical habitat, shortly followed by RB (COSEWIC, 2003; DFO 2014b). This designation provided legislative protection under *SARA*, *the Fisheries Act*, *Canada-Nova Scotia Offshore Accord Implementation Act*, *National Energy Board Act*, *Canada Shipping Act*, and *Canadian Environmental Protection Act*, to inhibit human activities that may result in the destruction of the habitat (SARA, 2009). In addition to protection from habitat degradation, a 2003 petition to reroute the shipping lanes in GMB to avoid the areas with the highest concentration of NARWs was approved by the International Maritime Organization (IMO; Vanderlaan et al., 2011). Then, in 2008 the IMO declared RB as an "area to be avoided" (ATBA): a rerouting system in which the navigation of the designated area is deemed "hazardous or exceptionally important to avoid casualties", thus all vessels are encouraged to avoid the area, or slow down if they must traverse the area (Davis et al., 2017; IMO, n.d.).

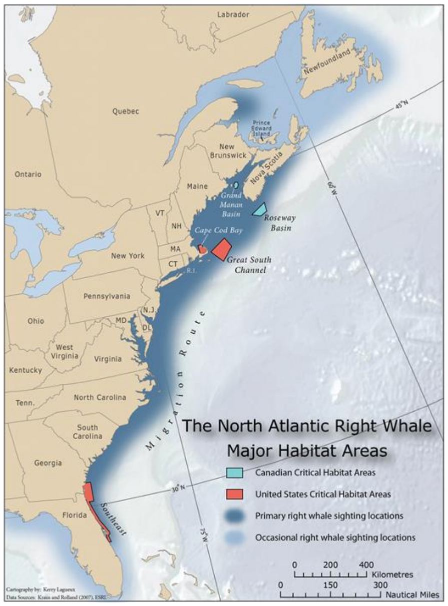
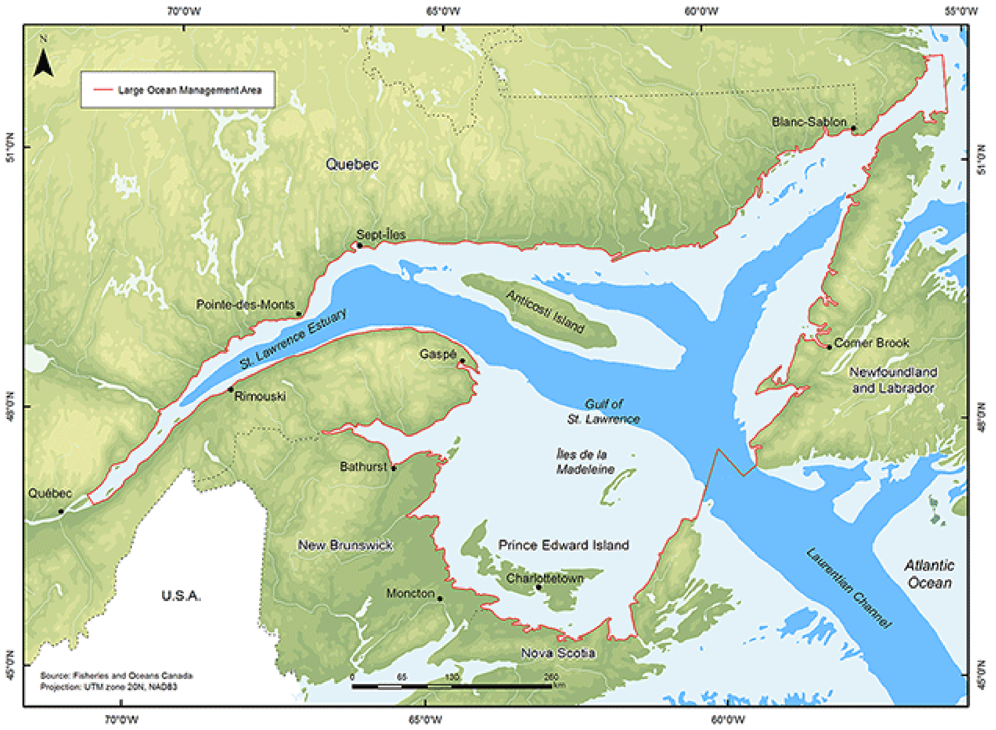


Figure 1.2 Distribution map of NARWs, indicating primary sightings and critical habitats (Hunt et al., 2015).

While conservation efforts have primarily focused on GMB and RB, in recent years researchers have found that NARW distribution has been shifting more North, with NARWs more frequently recorded than before in the Southern Gulf of St Lawrence (sGSL; Daoust et al., 2017; Davis et al., 2017). It is currently thought that this change in distribution is due to increasing water temperatures, resulting in their main prey of copepods, *Calanus spp.*, being found in larger concentrations in the sGSL; thus, it is thought that NARWs are following their food source (Daoust et al., 2017; Szabo, 2018). Consequently, this increase in NARW sightings in the sGSL brings new concerns relating to the human activities in the Gulf and NARW protection; therefore, this study focuses on the interactions that occur within the sGSL.

1.2. Gulf of St Lawrence

The Gulf of St Lawrence is a semi-enclosed sea and estuary ecosystem located in the Northwestern Atlantic Ocean (DFO, 2013b). It is enclosed by four provinces: Newfoundland and Labrador (NFL), Quebec (QC), New Brunswick (NB) and NS. It spans an area of approximately 240,000km^2 and encompasses the province of Prince Edward Island (PEI), as well as Anticosti Island and the Magdalen Islands; the sGSL refers to the marine area South of Anticosti Island, between QC, NB, NS and PEI (Figure 1.3; Dufour & Ouellet, 2007). The Gulf of St Lawrence is one of the largest and most productive marine ecosystems in Canada and worldwide, which connects the Atlantic Ocean to the Great Lakes watershed via the St Lawrence River (Dufour & Ouellet, 2007). As such, it creates a unique jurisdictional structure in which the area is governed by the five provincial governments, the federal government of Canada, multiple municipalities, as well as First Nations and Aboriginal groups (DFO, 2013b). This complex structure means there are close to 30 Acts and 100 federal regulations, 150 provincial regulations, and over 400 municipal bylaws and zoning in effect (DFO, 2013b).



Source: Fisheries and Oceans Canada
Projection: UTM zone 20N, NAD83

Figure 1.3 Boundary of the Gulf of St Lawrence management area (DFO, 2018b).

Due to the Gulf's productivity and the large population that lives along the coastline, the Gulf is used for a wide variety of human activities, including commercial fishing and aquaculture, marine transportation and shipping, coastal and marine tourism and recreation, and oil and gas exploration (Dufour & Ouellet, 2007; DFO, 2013b). Commercial fisheries in the Gulf includes over 50 different species, including several groundfish, pelagic fish and shellfish, as well as Canada's most lucrative fisheries: lobster, snow crab, and shrimp. Meanwhile, there are approximately 1800 different aquaculture sites situated around PEI, NS and NB. Moreover, the oil and gas industry has accumulated 60,000km of seismic data since the 1960s. Meanwhile approximately 6400 commercial vessels traverse the Gulf annually carrying goods from the oil and gas industry, forestry, mining, agriculture, and fisheries to over 40 major ports in the area. Finally, tourism and recreation use includes cruise ships, sail boats, and wildlife watching vessels, which adds to the already overcrowded waterways.

These activities have created huge stressors on the marine environment that may have significant negative effects on the biophysical and biochemical attributes of the Gulf, as well as on marine biodiversity (Dufour & Ouellet, 2007; DFO, 2013b). Consequently, a collaborative integrated management plan (IMP), operated by DFO under the *Oceans Act*, aimed at coordinating the different regional policies, regulations, operations and management of the Gulf through a risk-based management approach was implemented (DFO, 2013b). The IMP identifies the primary concerns in the Gulf as disturbances and noise pollution caused by seismic exploration and vessel traffic, biomass removal and overfishing from the commercial fisheries, chemical and disease contaminants from aquaculture pens and dredging, and collisions with other users and marine mammals from overcrowding and large vessels (Dufour & Ouellet, 2007; DFO, 2013b). Ultimately, the IMP is focused on preventing alterations to endemic biota and habitat that would change the structure, function and productivity of the area, caused by these anthropogenic activities (DFO, 2013b). The overall goal of the IMP is to develop an ecosystem-based management (EBM) plan following a precautionary approach to protect the marine environment and vulnerable species (DFO, 2013b). However, since prior to 2015 NARWs were only occasionally seen in the sGSL, the IMP does not identify NARWs as a current or primary species of concern, despite being at high risk from these activities (Dufour & Ouellet, 2007; DFO, 2013b).

1.3. Management Problem

Entanglement caused by fishing gear is a growing problem for marine species worldwide. Annually, an estimated 300,000 cetaceans die from entanglement, leading to conservation concerns, particularly with already threatened or endangered populations (IWC, 2018). NARWs are, in particular, highly susceptible to entanglement in commercial fishing gear, which is the leading cause of human-induced mortality, followed by vessel strikes (Kraus et al., 2016; Pettis et al., 2018). NARWs spend the majority of the time foraging and socializing within five meters of the surface of the water, making them difficult to see and susceptible to ship strike (Mayo & Marx, 1989; Parks et al., 2012). On the other hand, how NARWs become entangled is still is relatively unknown, but is thought to be contributed by the amount of fishing gear and rope in the water (Vanderlaan et al., 2011). Serious entanglements include rope wrapped around or in the mouth, around the tail or peduncle, and around the pectoral fins, with gear trailing behind the animal (Figure 1.4; Knowlton & Kraus, 2001; Knowlton et al., 2012). Entanglement can lead to drowning, systemic infection from intensive tissue damage, severe emaciation as a result from increase energetic costs of dragging fishing gear, and reduced mobility and foraging abilities (van der Hoop et al., 2014; 2016).

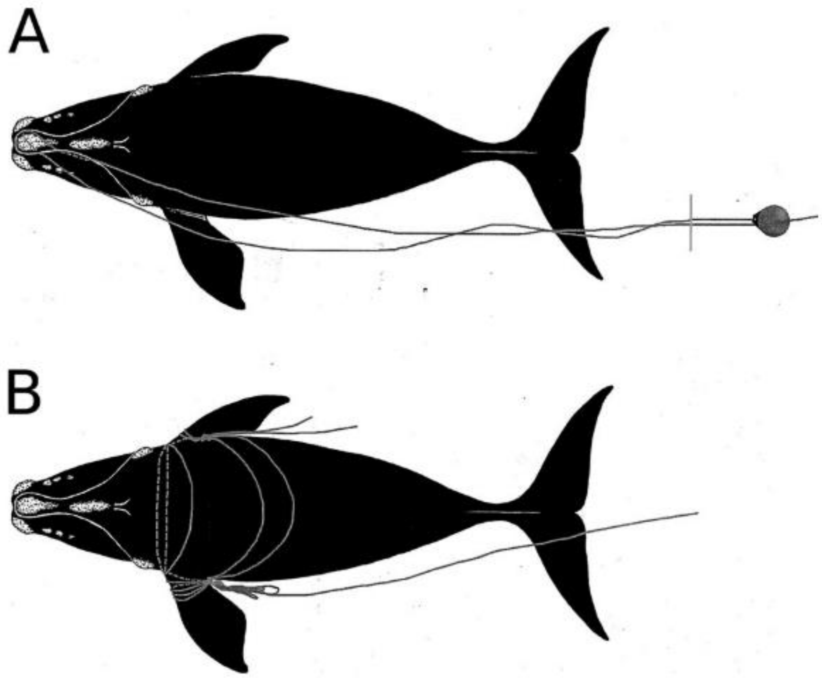


Figure 1.4 Illustration of different entanglement configurations on a NARW (van der Hoop et al., 2016).

In 2017, 17 NARWs were found dead, of which 12 were in the sGSL. Of these, eight were male and four were female, ranging from two to approximately 37 years old (Daoust et al., 2017). The large number of mortalities led the National Oceanic and Atmospheric Administration (NOAA) Fisheries department in the US to declare it as an unusual mortality event (UME; Figure 1.5); an UME is a designation under *MMPA* defined as “a stranding that is unexpected; involves a significant die-off of any marine mammal population; and demands immediate response”, aimed at increasing funding to investigating the event (NOAA, n.d-b; 2018a). Necropsies were performed on seven of the 12 NARWs and concluded that at least two deaths were directly linked to entanglement in Canadian snow crab fishing gear, likely as a result of acute drowning, and three were attributed to blunt trauma (Daoust et al., 2017). In addition to these deaths, another five NARWs were reported as actively entangled in the sGSL (Daoust et al., 2017). The necropsy results correspond with the large amount of fishing and shipping that occurs in the sGSL, highlighting the need to further asses and understand why NARWs are aggregating in the sGSL and how to manage human activities to prevent further deaths in the population (Daoust et al., 2017). In particular, management of the sGSL snow crab fishery has come under scrutiny due to the identification of their gear as a main contributor to these severe entanglement events.

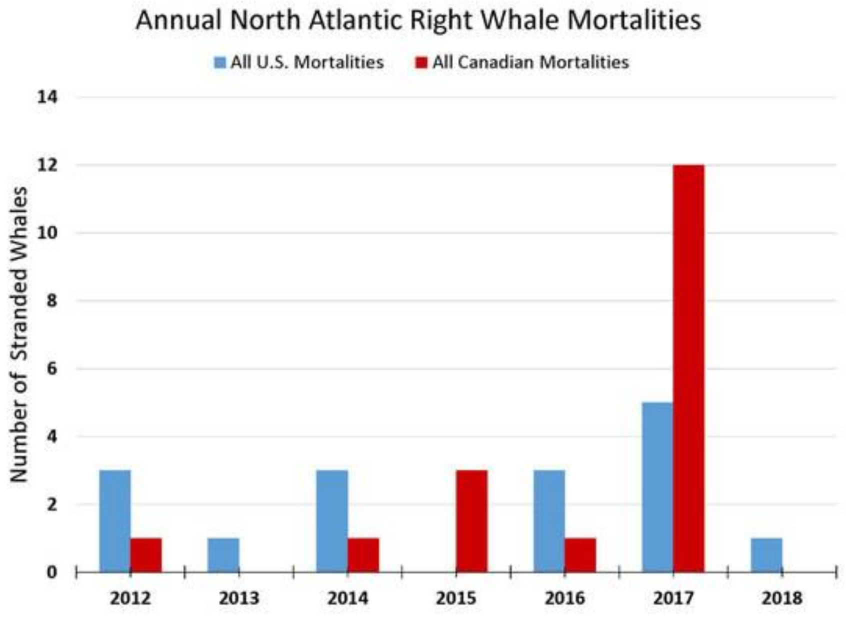


Figure 1.5 Annual Canadian and US NARW mortalities (NOAA, 2018a).

Snow crab, *Chionoecetes opilio,* is the second most lucrative fishery in Canada, with commercial landings valued at 592.7 million dollars; meanwhile lobster, *Homarus americanus,* is the most valuable Canadian fishery valued at over 2 billion dollars (DFO, 2018e). The sGSL snow crab fishery, located between QC, NB, NS and PEI, represents almost a quarter of all Canadian snow crab landings, with a value of 246.1 million dollars (DFO, 2018e). The fishery uses fixed pot or trap gear, which use ropes that connect a single trap at the seafloor with a buoy at the surface. It is believed this rope poses a high risk of entanglement for marine mammals (Brillant & Trippel, 2010). The snow crab fishing season also coincides with the increased summer sightings of NARWs in the sGSL. Consequently, following the 2017 mortality event, DFO implemented new management measures aimed at limiting interactions between NARWs and snow crab fishing gear, which include a shortened fishing season as well as static and dynamic fishing exclusion zones (DFO, 2018d).

The new management measures raised concerns from the fishers relating to the costs and impacts to the fishery, as well as the effectiveness of the measures to minimize the threat of entanglement (APPCA & ACA, 2018). Many fishers felt there would be severe economic impacts to the fishery as a result of spending more time at sea to catch the same quota, or perhaps not catching the entire quota (APPCA & ACA, 2018; Fahmy, 2018). Some believed that a static closure would result in a “fishing-the-line” scenario, in which the displaced fishing would move around the border of the exclusion zone, resulting in a heavy fence of fishing gear, effectively increasing the risk of entanglement (APPCA & ACA, 2018).

This research project aims to examine the estimated costs to the sGSL snow crab fishery, and the resultant effects to NARW protection of the 2018 management measures. A predictive model was developed to estimate fishing effort displacement from the fishing exclusion areas. A movement cost approximation of the displacement was used to determine the socio-economic impacts to the fishery, while conservation efficacy of the management measures was determined by calculating the change in co-occurrence, or threat, of NARWs and snow crab fishing gear in space and time. The model was then used to examine four different fishing closure strategies, in which the results were used to evaluate the concerns raised by the snow crab fishery and to make recommendations of the closure strategies which would minimize costs to the fishery while maximizing NARW conservation efforts. Additionally, this model provides a tool for adaptive management that can be altered based on changing NARW distribution, which can be further applied to other at-risk species and fisheries.

2. CHAPTER TWO: SNOW CRAB FISHERY

2.1. Species Biology

Snow crab is a crustacean, like lobster or shrimp, found in cold waters with muddy or sandy bottoms throughout the Northwest Atlantic Ocean, North Pacific Ocean, and the Sea of Japan (Davidson et al., 1985; Weston, 2011). Snow crab prefer waters with a temperature between -1 and 4 degrees Celsius (ºC), but can but found in waters as warm as 11ºC; however, it is thought that prolonged exposure to temperatures over 7 ºC can be detrimental to their survival (Davidson et al., 1985; DFO, 2016a). They can be found in a range of depths from 20m to 2000m, but are usually found at depths between 50m and 300m in the sGSL (DFO, 2016a). They feed upon a variety of different prey species including shrimp, capelin, starfish, sea urchins, worms, other crabs, molluscs, sea snails and sea anemones (DFO, 2016a).

Also known as queen crab, snow crab belongs to the spider crab family and is recognized by its large, flat, almost circular body and five pairs of long legs (Figure 2.1; Davidson et al., 2011; CSAS, 2018). They have an estimated lifespan of 12-13 years in which their colouration changes as they age; younger, freshly molted crab will be reddish in colour with a white underside which fades to an olive colour with a yellowed underside as they age (DFO, 2016a). They are sexually dimorphic with males growing twice the size of females to a maximum carapace width of 15-16cm and weighing up to 1.35kg, while females often only reach 9.5cm and 0.5kg (Weston, 2011; DFO, 2016a). Females will lay between 16,000 and 160,000 eggs which are incubated for up to two years before the larvae are dispersed through the water column into open water (Weston, 2011; DFO, 2016a). Unlike lobster, snow crab do not molt throughout their lifetime, instead undergoing a terminal molt at sexual maturity for females, and for males when they grow large claws, which can happen anywhere between 4-15cm carapace width (Davidson et al., 1985; CSAS, 2018). It can take up to 10 months for a crab's new shell to harden following a molt, during this time they are considered soft-shell or white-crab and are susceptible to predation from species including halibut, skates, cod, seals, squids, and other crabs (Weston, 2011; DFO, 2016a). A crab can live up to six years after its terminal molt under optimal conditions, thus females may be able to breed more than once (DFO, 2016a).

Figure 2.1. Illustration of a snow crab (DFO, 2016a).

2.2. Development of the Commercial Fishery

Snow crab was first landed in the sGSL as incidental bycatch from the groundfish industry in the 1960s (DFO, 2014a; 2016). This led to the start of a small, seine fishery off of Chéticamp, NS in 1965 that expanded to NB, PEI and QC by 1968 (Pinfold, 2006; DFO, 2014a). At this time fishers started using baited traps (i.e. pots) and concentrated in the waters around Gaspé, QC and Cape Breton, NS (DFO, 2014a). New fishing grounds were continually discovered, and the fishery continued to expand, becoming a major fishery in the late 1970s, bringing about the first management measures (Pinfold, 2006; DFO 2014a). These measures included better policies to define the fishing fleets, defining the crab fishing areas (CFA) 12, 18, 19, 25 and 26, as well as effort control measures to prevent overexploitation (DFO, 2014a). By 1982 annual landings were reaching 35,000 tonnes, exploited by 130 vessels from QC, NB, NS and PEI, now known as the traditional fleet (Weston, 2011; DFO 2014a). By 1990 landings had reached an all time low of 10,000t, at which time more management measures including quotas and stock assessments were implemented as DFO became more concerned about the conservation and overexploitation of the species; the new management measures resulted in positive impacts and a steady rise in landings (Weston, 2011; DFO, 2014a).

In the mid-1990s a sharing program was created to allow non-snow crab fishers (known as the new-access fleet) to profit from the lucrative fishery; moreover, two new new exploratory zones, CFA 12E and 12F, were also developed (DFO, 2014a). Additionally, a co-management regime was created for CFAs 12 and 19 in order to help with cost sharing (DFO, 2014a). Following the Marshall Decision ruling in 1999, a retirement plan for licences in CFA 12 were implemented to allocate more access to First Nations (Weston, 2011; DFO 2014a). However, this process did not allow for sufficient shares for the First Nations, therefore a relocation of quota was divided amongst the traditional fleet, new-access fleet and First Nations fleet in 2006. By 2003, CFA 12E and 12F were opened to commercial fishing, and CFAs 12, 18, 25 and 26 were managed as one unit (Westin, 2011; DFO 2014a). Finally, in 2010 DFO began to implement a precautionary approach to the fishery, aimed at maintaining healthy stocks by promoting rebuilding when catch is poor, and a moderate level of exploitation when stocks are healthy (DFO, 2014a).

2.3. General Management Measures

The fishery is divided into seven CFAs: 12, 12E, 12F, 18, 19, 25 and 26, and includes two buffer zones (closed to fishing), 18 and F (Figure 2.2; DFO, 2014a). As stated above, CFAs 12, 18, 25 and 26 have been managed as a single unit since 2003, therefore, hereafter they will be referred to as CFA 12 (DFO, 2014a). Each CFA encompasses the waters enclosed by plotted rhumb lines (straight line between nautical coordinates) and/or the coastline (DFO, 2014a). The boundary rhumb lines connect a series of latitudinal and longitudinal coordinates which can be found in Appendix A (DFO, 2013a; DFO, 2014a).

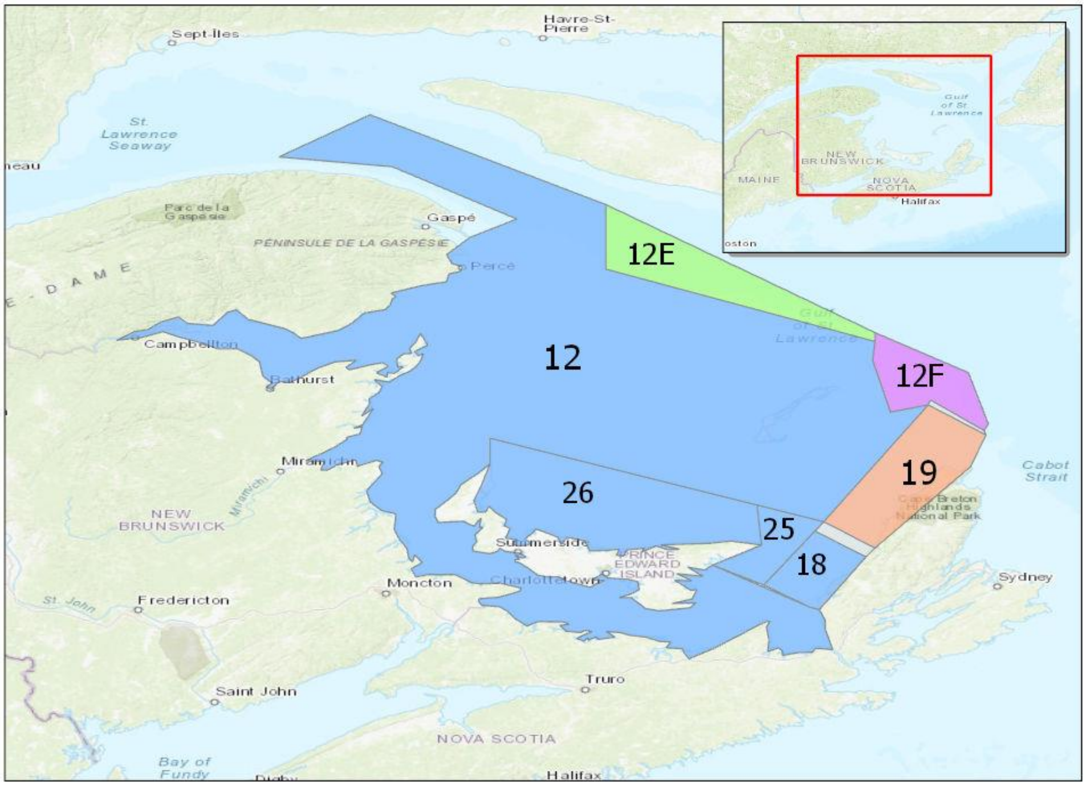


Figure 2.2 Management areas of the sGSL snow crab fishery. The grey sections on either side of CFA 19 represent the two buffer zones, F (top) and 18 (bottom).

In addition to the defined CFAs, the entire sGSL is divided into 10º grids for the purpose of monitoring and managing soft-shell crab exploitation rates (Figure 2.3). Fishers are only allowed to catch male crabs with a minimum carapace width of 9.5cm, females and soft-shell crab are not to be kept; male crabs of commercial size, but with small claws are also allowed to be returned as this is indicative of an immature male. Consequently, there is a soft-shell crab protocol in place that dictates that if the catch for any given grid cell exceeds 20% soft-shell crab, it is closed to fishing for the remainder of the season. The purpose of this protocol is to prevent the overexploitation, handling, and at-sea discarding of this vulnerable life stage. This protocol is enforced by DFO and is applicable to all CFAs in the sGSL. There is a total of 509 unique grid cells that fall within the sGSL snow crab fishery region. The grids cells are identified based on an alphabetized and numbered identification system in which each grid is indexed longitudinally based on letters and latitudinally on numbers, ranging from GO to HL and 22 to 58 (e.g. GX40; Figure 2.3).

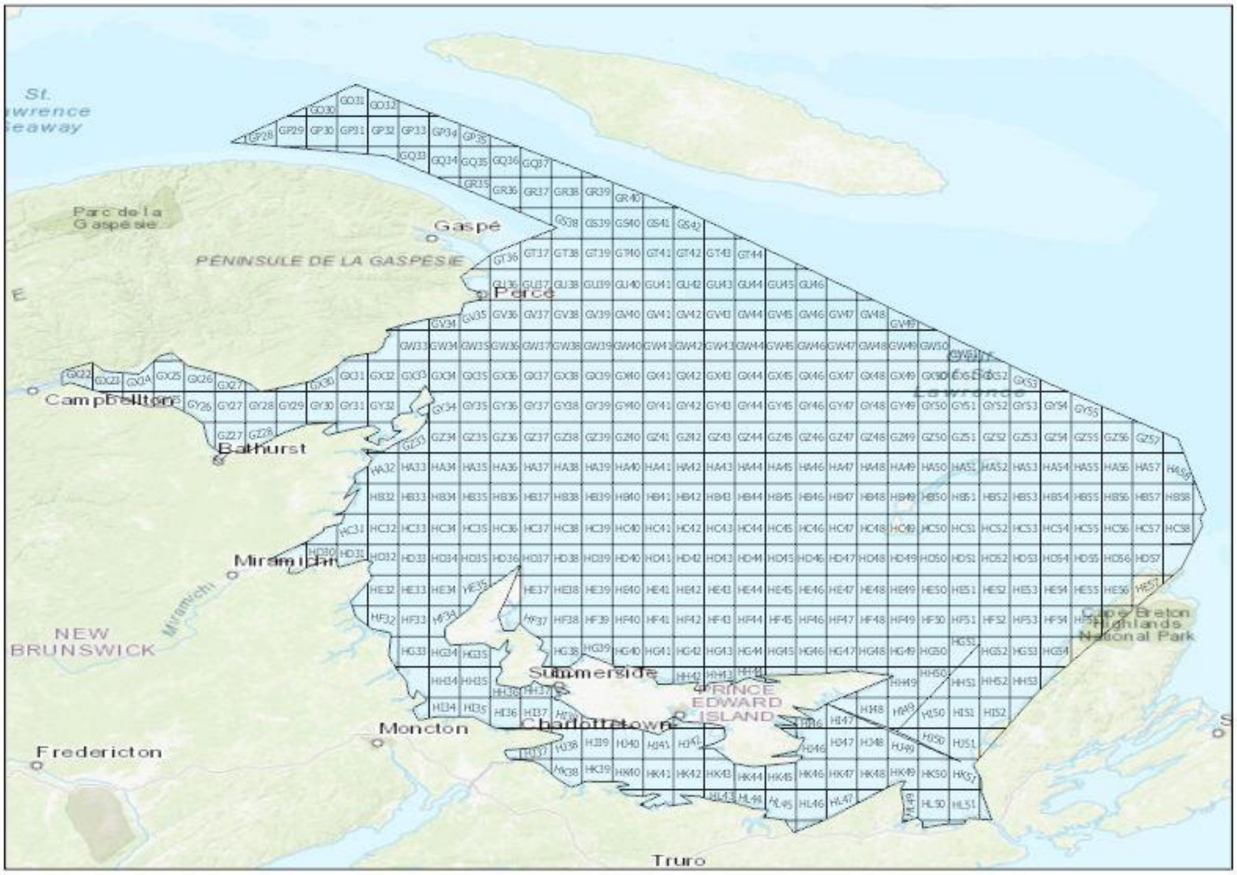


Figure 2.3 Soft-shell crab protocol grid cells.

The sGSL snow crab fishery uses a variety of effort control measures to manage the fishery. First, a total allowable catch (TAC) is determined annually, based on stock assessments, to determine to total tonnage of crab that may be caught in a given year (DFO, 2014a, CSAS, 2018). The TAC for CFA 12 is divided between the traditional fleet, new access fleet, and First Nations fleet of the four surrounding provinces as 70%, 15% and 15%, respectfully. The traditional fleet refers to the vessels that were present before 1990 and includes a midshore and inshore fleet; midshore vessels are typically between 65’ and 100’, while the inshore fleet is vessels less than 65’ in length. (DFO, 2014a). Furthermore, the new access fleet refers to those who have a secondary licence for snow crab and includes groundfish, lobster and scallop fishers for all four provinces, while the First Nations quota is divided between NB, QC and PEI (DFO, 2014a). The TAC for CFA 12E is divided between NB, QC and PEI as 75%, 12.5%, and 12.5%, and CFA 12F is divided between QC and NS as 68.75% and 31.25%, respectfully (DFO, 2014a). CFA 19 follows an individual transferable quota (ITQ) system where one trap is equal to one share of the TAC, where the total number of traps available is 1,699, and is based out of Cape Breton, NS (DFO, 2014a). The full breakdown of the TAC for all CFAs can be found in Appendix B. The sGSL fishery also operates on a seasonal basis. CFAs 12, 12E and 12F open once the winter sea ice has thawed, typically towards the end of April, and is open until mid-July (DFO, 2014a). Meanwhile, CFA 19 is open from mid-July until mid-September (DFO, 2014a). In order to have access to the fishery, a harvester must hold a valid snow crab licence which is granted by DFO under the *Fisheries Act*, and all vessels and crew must be registered with DFO (DFO, 2014a).

To ensure the soft-shell crab protocol, male only catch, and quota regulations are being complied with, the fishery further implements trap limits, gear restrictions and catch monitoring regulations (DFO, 2014a). Each CFA employs its own trap limits based on the available quota and the different fleets. Prior to 2017, in CFA 12, the midshore fleet was allotted a maximum of 150 traps per licence holder; 75 traps for the traditional inshore fleet (primarily from PEI); 75 traps for those operating within CFA 18; and the new-access and First Nation fleets were given 75 traps if they received quotas up to 50t, meanwhile, those with quotas over 50t are able to use 150 traps (DFO, 2016b). CFA 12E trap limits are based on ITQ amounts: an ITQ of up to 45t allows a harvester 100 traps; between 45t and 68t allows for 125 traps; between 68t and 90t allows 150; and, over 90t allows for 175 traps (DFO, 2016b). Meanwhile, in CFA 12F, prior to 2017, there was no mention of quotas or ITQs, but rather a standard maximum of 75 traps for all licence holders in the area. Finally, in CFA 19, as stated above, the quota and trap shares are directly related. There is a maximum of 1,699 traps allowed in the CFA and each trap is the equivalent of one trap share, or 0.983t (DFO, 2016b). In 2017, there was double molt event in which the crab that did not molt in 2015, molted in 2016, resulting in a large increase in biomass for the 2017 fishing season (The Telegram, 2017). The TAC for 2017 was doubled, and subsequently trap limits were increased in CFAs 12 and 12F, while the trap limits in CFA 12E and 19 remained unchanged (DFO, 2017; The Telegram, 2017). In CFA 12, trap limits were divided based on the quota of the TAC of each licence holder, rather than the fleet in which the belonged to. As such, licence holders with less than 0.22% of the TAC were allotted 75 traps, which primarily included the inshore PEI fleet, CFA 18, and new-access licence holders with ITQs, meanwhile, those who hold more than 0.44% of the TAC, such as the traditional midshore fleet, were given 174 traps (DFO 2017b). The other new-access fleets, and the First Nations fleet were authorized to have one trap per 0.54t of the TAC, to a maximum of 174 traps per licence holder (DFO, 2017). Meanwhile, in CFA 12F, a trap limit per quota share was developed: those with less than 11.34t of the TAC were limited to 35 traps; between 11.34t and 18.14t were given 50 traps; between 18.14t and 31.75t are allowed 65 traps; and, those with over 31.75t were allowed a maximum of 75 traps (DFO, 2017).

In terms of the gear itself, all traps must have a maximum mesh size of 75mm and cannot exceed a volume of 2.1m^3; traps must also include identification information and tags. In order to monitor at-sea operations, a satellite vessel monitoring system (VMS) is mandatory, in addition to a hail out and hail in protocol when sailing in or out of port. Vessels are also subject to at-sea onboard fisheries observers to make sure that catch restrictions are being enforced. Meanwhile, a 100% dockside monitoring system, that uses digital scales to record landings (in kilograms), and logbooks, filled in by the vessels to record landings and fishing effort information, ensures TAC and quota compliance. Consequently, these combined efforts supported a sustainable fishery, and in 2012 the fishery was rewarded a Marine Stewardship Council (MSC) certification (DFO, 2014a). The MSC certification is an independent third-party process that rates a fishery based on the sustainability of the fishing practices and fish stock, the fishery's environmental impacts to the environment, and how well the fishery is managed (Ponte, 2012). It allows for product from the fishery to be labeled with the MSC logo so that consumers know that it comes from a sustainable, environmentally sound fishery (Ponte, 2012). It creates access to more markets such as Loblaws in Canada and Wal-Mart in the US, as well as throughout Europe who exclusively sell MSC certified seafood (DFO, 2014a). However, following the 2017 NARW mortality event, MSC suspended the sGSL snow crab certification and gave them 90 days to develop a corrective plan in order to be re-certified (O'Connell, 2017; Withers, 2018).

2.4. Management Measures for NARW Protection

Following the 2017 NARW mortality event that found a direct correlation between commercial snow crab gear and lethal entanglement of NARWs in the sGSL, and resulted in the loss of their MSC certification, DFO implemented a series of new regulations for the 2018 fishing season. These new regulations were aimed at reducing interactions between the fishery and NARWs in hopes of increasing protection for NARWs in 2018. All prior regulations, as outlined in section 2.3, remained in effect, however some measures were altered, while other new regulations were created.

Regulations that were altered focused on the monitoring, gear limits and restrictions, and dates of the fishing season (DFO, 2018d). Firstly, VMS reporting must now be at five-minute intervals, and should be registered with DFO for all CFAs. For gear, several changes were implemented including minimizing the amount of surface rope on the water, so that the length between the primary buoy (attached to the pot) and the secondary buoy (attached to the primary buoy) is no more than 3.7m. Additionally, rope between the primary buoy and the pot is not allowed to be floating on the surface once the trap has been deployed; the purpose of this is to reduce the amount of rope in the water to reduce the risk of entanglement. Meanwhile, other modifications were developed to improve identification of traps so that in the case of an entanglement it will be easier to identify the fishery and/or sector of origin (Figure 2.4). These included specific coloured markings on the rope between the trap and primary buoy, and added identification markings. Coloured rope markings should be permanent and in 15cm segments along the length of the rope at a minimum distance of 27.5m apart; markings should be orange for CFA 12, yellow for CFA 12E, and blue for CFA 12F. The identification buoys will include the vessel's registration number (a prior regulation) as well as identify the primary buoy with a sequential number to individually identify each trap. Finally, the fishing season for CFA 12, 12E and 12F was set to close on June 30, rather than in mid-July, while the season for CFA 19 was not impacted. NARWs are typically seen in the sGSL starting in May and June, with July through September having the most sightings, thus closing the fishery early was aimed at removing all gear from the water before the majority of NARWs entered the sGSL. In order to compensate for closing the fishery early, efforts were also made to open the fishery as early as possible, dependant on sea ice conditions.

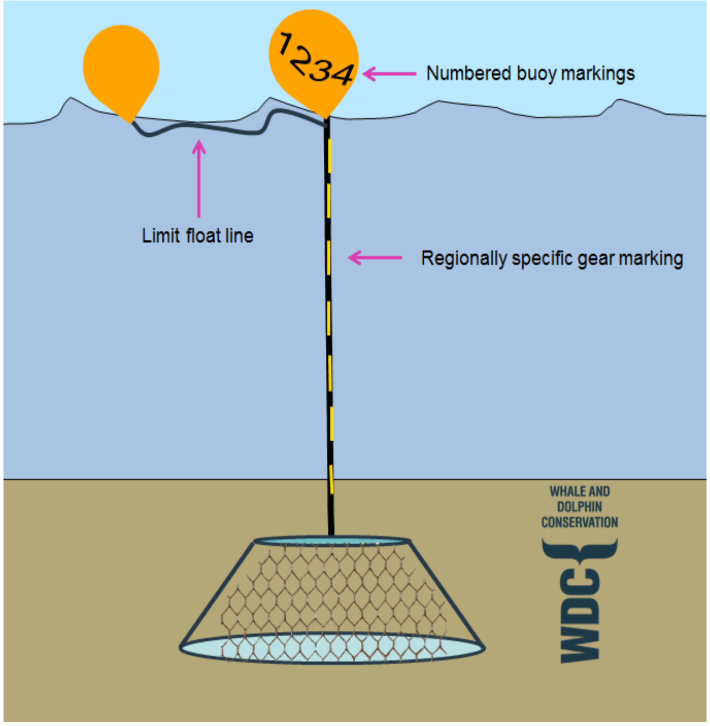


Figure 2.4 Pot trap configuration for the sGSL snow crab fishery with 2018 gear modifications (WDC, 2018).

Trap limits for CFA 12 were also altered again, this time in an effort to reduce the amount of gear in the water as a means to reduce the risk of entanglement (DFO, 2018d). Licence holders in CFA 12 holding less than 0.22% of the TAC may still have a maximum of 75 traps, however those holding more than 0.44% of the TAC may now only have 150 traps, which is also the limit for the First Nation fleets as well as the new-access fleets who distribute their TAC based on ITQs (down from the 174 traps they were allotted in 2017). Thus, the regulations for NARW protection changed the 2017 trap limits back to the amounts that were allotted in the years prior (2016 and beyond). Meanwhile, CFAs 12E, 12F and 19 all remained the same as the 2017 trap limit regulations, following the same quota breakdowns.

DFO also required a number of new mandatory reporting regulations to further assist in the reduction of risk of entanglement and lethality of entanglement (DFO, 2018d). This included mandatory reporting of any lost gear, as a way to help quantify the annual amount of lost gear and identify areas that require increased efforts of retrieval. Additionally, it is now required that any sightings or interactions with marine mammals be reported. This means that any sightings of collisions, entanglements or bycatch of any marine mammal be reported immediately to DFO. A marine mammal interaction form is then to be completed and submitted to DFO within 48 hours of returning from a fishing trip to further quantify injury and mortality as a result of fisheries interactions. Further, all live sightings of freely swimming NARWs were also to be reported to DFO as surveillance effort and to assist in population and distribution estimates.

While the above changes are relatively simple alterations to previous management measures, the primary changes to the fishery include the introduction of a static fishery closure, or exclusion zone, and three dynamic management areas (DMA; Figure 2.5; DFO, 2018d). Using the existing soft-shell crab protocol grid system, the outlined static closure – encompassing the area in which 90% of the 2017 NARW sightings were reported, was closed to all fishing activity for the entirety of the sGSL fishing season. The purpose of this static closure was to provide a large gear free area in the most likely area that NARWs were expected aggregate. There is a total of 28 individual grid cells within the static exclusion zone, which only effects CFA 12. Meanwhile, the DMAs refer to three separate large areas in which any grid cells with the respective DMA could be closed by DFO as a result of a single NARW sighting; a DMA closure is the respective closed grids within the DMAs. The three DMAs were also determined based on the 2017 NARW sightings, and were found in both CFA 12 and 19. Closures in the DMAs also operated using the soft-shell crab grid system, in which specific grids would be closed based on real-time sightings of NARWs. When a NARW was seen, the grid cell in which it was observed, as well as a 1 grid cell buffer surrounding the whale, for a total of 9 grid cells, closed to fishing for a minimum of 15 days. Fishers were to be given at least 48 hours notice of a DMA closure to allow them time to remove their gear before the closure went into effect. Regular aerial surveys of the area were to be conducted, and if a whale was no longer seen in the closed grids for the last two surveys, then the respective grids would reopen after the minimum 15-day period. However, if a NARW continues to be seen in the closed DMA grids, the closures would be extended for another 15 days until NARWs were no longer seen in the area.

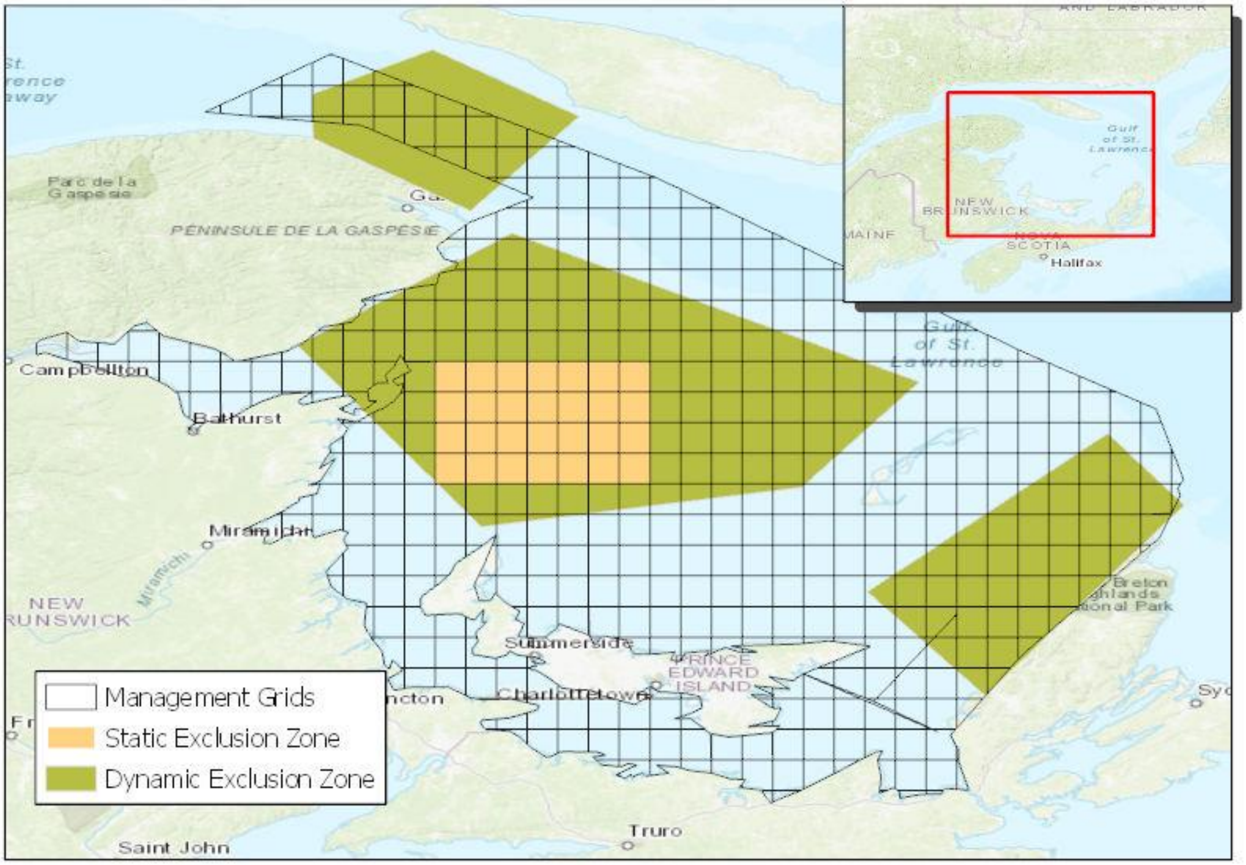


Figure 2.5 Static exclusion zone and DMAs using the soft-shell crab grid system.

2.5. Fishery Operations and Fleet Behaviour

Since its inception, the sGSL snow crab fishery has become an economically and culturally important fishery to the area and worldwide. Of the 30-crab species fished worldwide, snow crab represents 14% of all global crab landings as of 2010; Canadian landings representing approximately 43% of these global landings (DFO, 2014a). Canadian snow crab is mainly exported to the US and Japan, which has resulted in the fishery becoming the second most lucrative fishery in Canada valued at 592.7 million dollars (DFO, 2018e). The market price of snow crab fluctuates depending on the global market and supply, but has been on an upward trend, with the Canadian snow crab value increasing annually. In Canada, snow crab is only fished in Atlantic Canada, in which the sGSL represents approximately 37% of the total landings, representing almost 42% of the total revenue of the fishery ($246.1 million as of 2016; DFO 2018e, 2018f).

Snow crab is a relatively stable fishery which follows a natural fluctuation in biomass; there have been four periods of high landings: 1981-1985, 1993-1997, 2004-2008 and 2009-2012

(CSAS, 2018; DFO, 2014a). Since the fishery employs a precautionary approach, the annual TAC follows the same fluctuation pattern where biomass is exploited at a reasonable rate during the periods of high biomass, and a low TAC during the low biomass years to support stock regeneration. Over the past nine years the average annual TAC ranged from 18,000t – 20,000t, with the TAC being fully caught by the fleets every year. Annual reports from the Canadian Science Advisory Secretariat show that the effort put into the fishery, in terms of trap hauls (number of trap retrievals) and the average kilogram of crab caught per trap haul, indicates that effort also reflects the overall TAC of each season, with lower effort in years with a lower TAC. In addition, soft-shell crab rates have also historically been consistent, with higher incidents of soft-shell crab and subsequent grid closures in the years with low TACs (to be expected as a low biomass would be reflective of a large molt); as such it remains a relatively stable fishery (see Appendix C for annual fishing performance for all CFAs).

This stability, along with the economic performance of the fishery, makes it an attractive industry to gain entry to, as such snow crab supports hundreds of fishers and thousands of processing and support jobs (DFO, 2014a). A typical vessel will employ one captain and approximately four crew members staying out at sea for three to four days at a time; for the smaller inshore vessels, who instead undertake daily trips, will typically have just the captain and one crew member (DFO, 2014a). Each province varies in its contribution to the fishery, as measured by the number of licences, reported landings, and economic value (Figure 2.6). 2016 reports indicate that Quebec holds the highest number of licences (382), and subsequently reports the highest landings (14,538t) and economic value (111.2 million dollars; DFO 2018e, 2018f, 2018g).

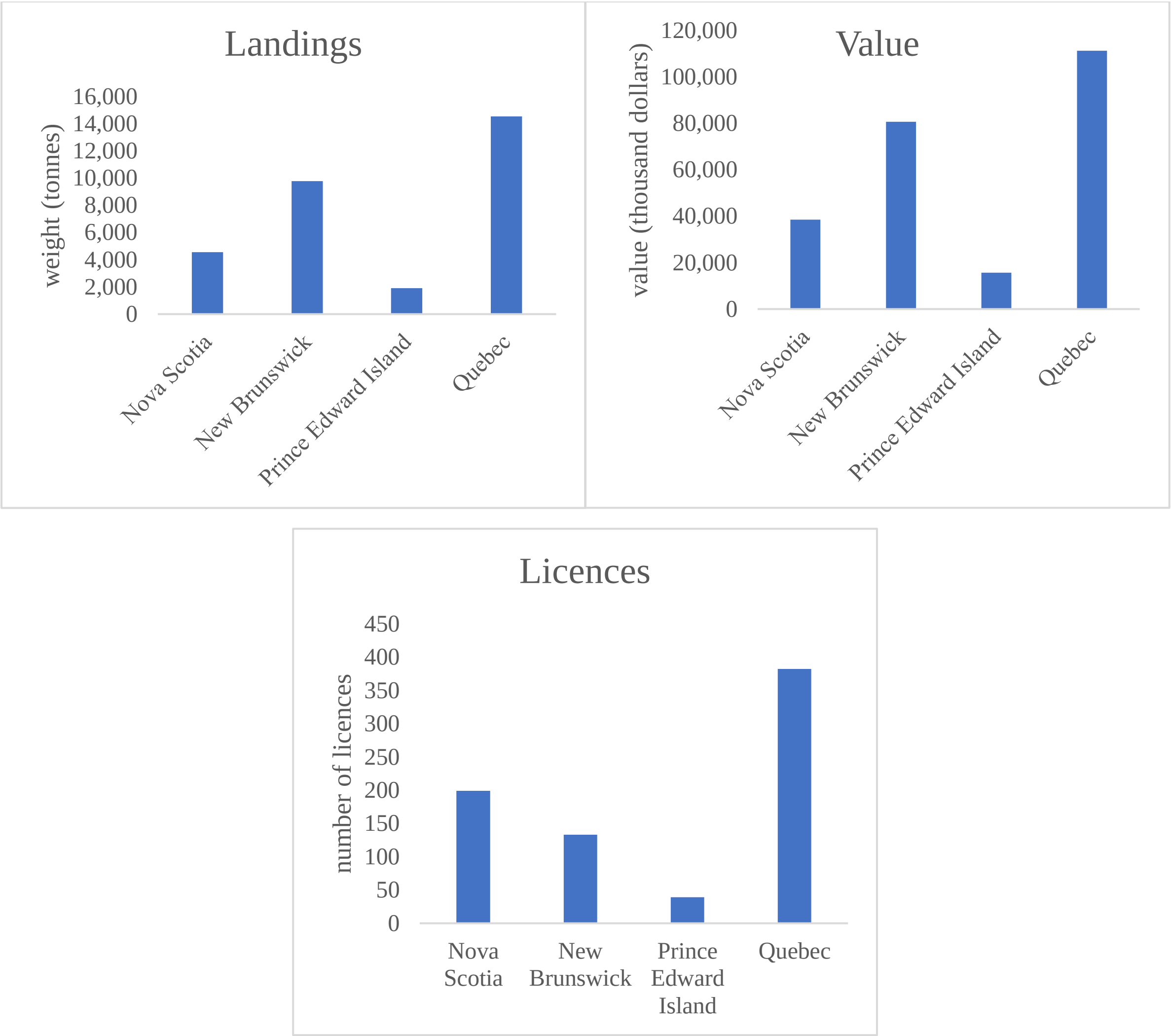


Figure 2.6 Landings (tonnes), value (thousand dollar), and number of licences within each province within the sGSL snow crab fishery (DFO 2018e, 2018f, 2018g)

The fishery can also be examined based on the CFA management areas, rather than by province. CFA 12 is considered the most productive (holding 91% of the overall TAC of the sGSL), which is not surprising given the size of CFA 12 and that all four provinces fish within this area, followed by CFA 19, 12F then 12E. Moreover, it is also important to examine the seasonal productivity in order to better understand operations and fleet behaviour (Figure 2.7). May is the most productive month, which, on average, accounts for 50% of the entire season's landings. June is the second most productive month, followed equally by April and July. Therefore, we can infer that the majority of all fishing effort occurs within the month of May; April and July are the most variable due to being the beginning and end months of the season and tend to be open for shorter periods compared to May and June. Meanwhile, with the introduction of the static exclusion zone, May is the second most impacted month, where 38% of the monthly landings fall within the boundary of the closure; April is the most impacted, yet seasonally variable, with an average of 43% of the monthly landings in the static closure; June is also relatively impacted at 25%. A small portion of July effort falls within the boundary of the static closure, however since the 2018 fishing season ended on June 30, all July fishing in CFAs 12, 12E and 12F will end and only occur in CFA 19, and not impacted by the static closures; August and September fishing also only occur in CFA 19 thus will also not be impacted by the static closures.

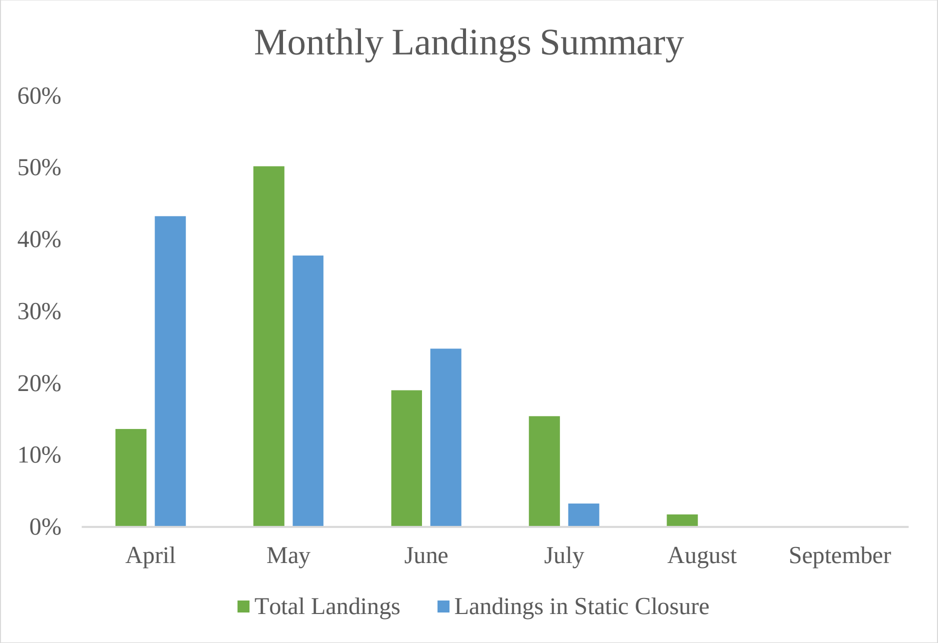


Figure 2.7 Monthly averages of annual landings and percentage of monthly landings within the static exclusion zone.

3. CHAPTER THREE: METHODOLOGY

3.1. Data

Fishing data was received from DFO for the years 2005 through 2012 (i.e. 8 years). This data included the number of sets (number of traps) and landings (tonnes) recorded at GPS positions (latitude and longitude) throughout the sGSL fishery. Additional data for 2013 to 2016 was also obtained, but did not contain information regarding landings; thus, this data was excluded from the analysis. As the different CFAs are open during different months, data included observations from April to September. However, this study primarily focuses on the management of CFA 12, due to its containment of the static exclusion zone, the number of dynamic closures and NARW sightings. Thus, this study focuses only on fishing activity that occurs from April through June (i.e. 3 months) since fishing in CFA 12 ends on June 30 based on the 2018 management measures.

The fishing data was examined and formatted to keep the date (day, month and year), landings (tonnes), sets (number of traps), and position (latitude and longitude). Data that reported landings, but no sets were removed. This study uses a weekly temporal resolution, in which the datasets were broken down into four weeks per month by year; to maintain consistency among years, week one consists of days one through seven, week two is days eight to 15, week three is days 16 to 23 and week four is day 24 to the end of the month, either 30 or 31. Once formatted, the fishing sets were summed into the soft-shell management grids (Figure 2.3) using ArcGIS Pro (version 2.2.3).

A GIS shapefile containing the geographical coordinates of the softshell crab management grids was provided by DFO, and uses the world geodetic system (WGS) 1984 for its geographical positioning; therefore, WGS 1984 was used as the standard for all mapping purposes of this study.

Fishing effort was averaged for each week across all years to determine a generalized average distribution of fishing. In order to standardize effort across all years, catch per unit effort (CPUE) was calculated for each grid cell.

$$\boldsymbol{CPUE = \frac{C_i}{E_i}} \tag{1}$$

Where *C* represents the catch, or landings, in tonnes, *E* is the effort, or number of sets in a given grid cell (*i*). Average CPUE and the standard deviation (to determine variability) was calculated for each grid across all years.

NARW sightings data was obtained from the Marine Environmental Observation Prediction and Response Network (MEOPAR) Whale Habitat and Listening Experiment (WhaLE). Data included the geographical location, date and time, and number of whales seen for each recorded sighting. The dataset included all confirmed sightings in the sGSL from 2015 to 2017; data from 2018 was not available at the time of completing this report, thus could not be obtained for the purposes of this study. 2017 had the most complete surveys of the sGSL of the available data, thus only sightings from this year were used for analysis. NARW sightings data was formatted to follow the same weekly resolution as the fishing data and summed into the soft-shell crab grids.

3.2. Displacement Model

A displacement model was created in R (version 3.5.1) using a series of rules and assumptions in order to follow a workflow process to determine the mostly likely grid cell a displaced grid will move to following a closure. First, this study uses a displacement model, which assumes that only the fishing activity in a closure moves, and the fishing in the open areas does not move as a result of the displaced effort, rather than a redistribution model in which both the fishing impacted by the closures and the fishing in the open areas move as a result of the closure, so that both move to adjust to a new equilibrium (Powers & Abeare, 2009). Therefore, the model assumes a modified ideal free distribution (IFD), in which individuals will move to a different area based on its suitability, but the destination areas do not limit the number of entrants (Powers & Abeare, 2009). Thus, in this case, an individual seeks a location that maximizes their return (based on CPUE; Powers & Abeare, 2009). Since, this model assumes that any effort displaced by a closure will move to an available location without impacting the non-displaced fishing, it also assumes that the fishing in the new location remains in equilibrium, despite additional effort moving into the location, and that the original CPUE of that area remains unchanged. Finally, the model follows both a one-step and multi-step movement cost process as outlined by Powers and Abeare (2009), depending on the closure scenario. A one-step process is used for displacement from static closures, as cost is determined based on the original distribution, whereas a multi-step process is applied to dynamic closures where cost is recalculated after each movement based on the previous location.

Following these assumptions, the model processes the averaged weekly data through a series of steps to determine the movement of the displaced fishing effort (Figure 3.1). First, the grid indices of all closed grid cells are defined as the “closed grids”. The indices are then compared to all fishing activity that occurred during the week. If no fishing activity occurred in any of the closed grid cells, then that week was not impacted by the closures. If there is fishing that is impacted by the closures, then the grids that are displaced (fall within the defined closed grids), as well as all grids open to fishing (must have observed activity in them and do not fall within the closed grids) are defined. The distance in kilometers between the displaced and open grids are then determined using the haversine formula (Esri Geonet Community, 2017).

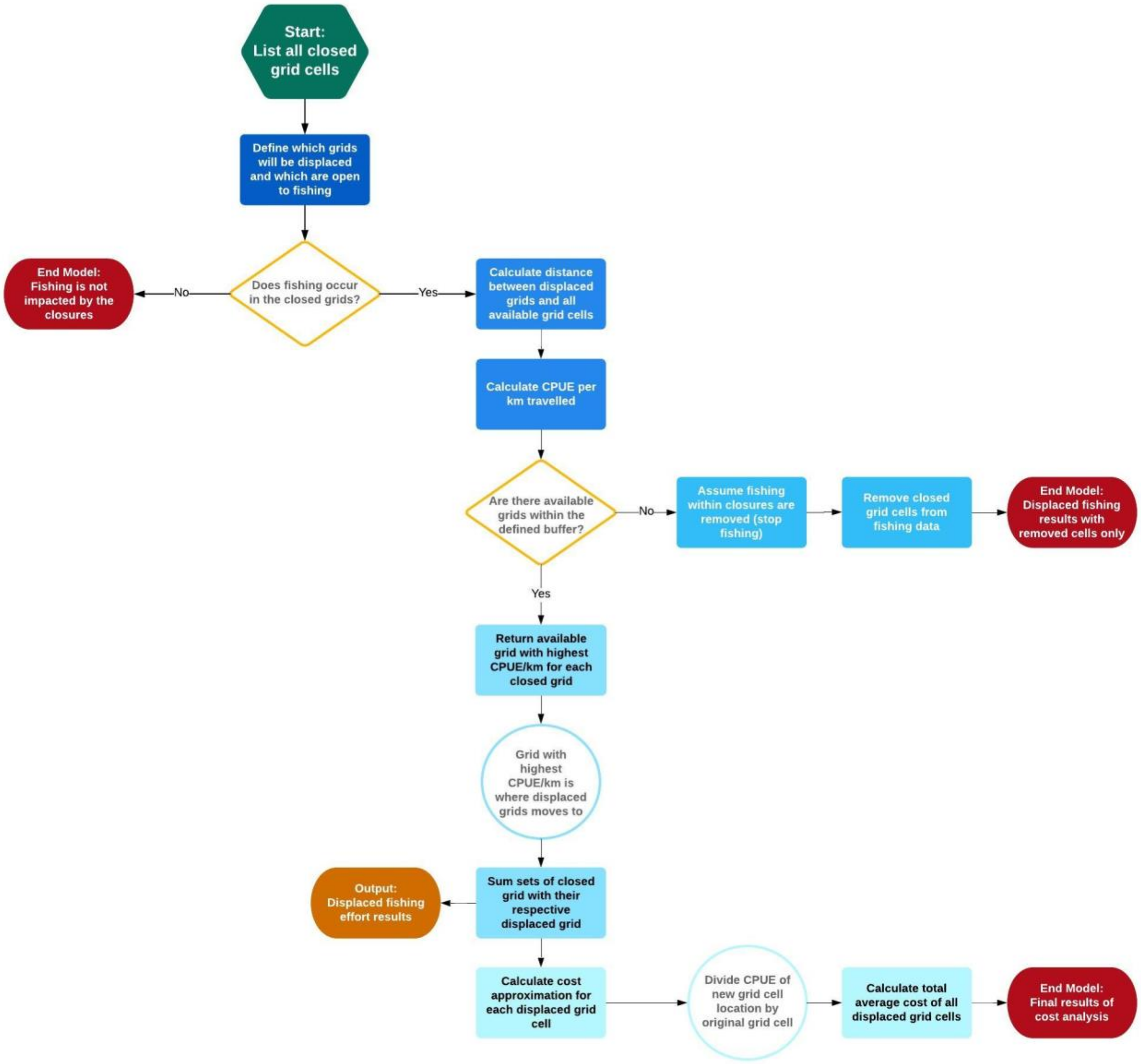


Figure 3.1 Displacement model workflow. The green hexagon represents the start of the model decision process, each rectangle represents the next step or calculation to achieve an output. The diamonds denote a yes or no decision that will either stop the model or continue to the next step. Circle highlight how the results of a step are determined, followed by the ovals which signify an output. The red ovals indicate the end of the model, while an orange oval indicates an output, while still continuing the workflow process.

A maximum travel distance of 60km to reach a new location was set based on an estimate of vessels travelling at 10 knots, adding approximately three hours of travel time and the associated costs of displacement. Therefore, open grids further than 60km from the displaced grids' original location were removed and not considered as an option for displacement; anything beyond this distance was assumed to be too costly, thus excluded as an option. If there were no available grids within this distance, it was assumed that the fishing in the impacted grids would stop fishing altogether and remove itself from the fishery (and subsequently, the model).

In order to determine the destination grid of the remaining displaced cells, the suitability, or CPUE per kilometer travelled was calculated as

$$\boldsymbol{S_j} = \left(\frac{\boldsymbol{Cj/Ej}}{\boldsymbol{d_{ij}}}\right) \tag{2}$$

Where S is suitability, C_j/E_j is CPUE of the destination grid (j) and d_{ij} is the distance between the displaced grid (i) and the destination grid (j). Suitability was used to determine the destination grid and indicates the estimated tonnage an individual would catch for each extra kilometer travelled. Therefore, the best destination grid for each displaced grid was determined as the available grid with the highest suitability. At this point, if all displaced fishing was removed from the model due to no available destination grids, then the model would stop, providing an output with no changes, other than no more fishing in the closure area. The model would then move to the next week and start over from the beginning. If fishing was displaced (i.e. moved out of a closed grid) and not removed (i.e. from the model entirely), then the displaced sets were added and summed with the existing sets in the destination grid.

3.3. Cost Analysis

Costs associated with the displaced fishing effort were calculated based on an approximation, as outlined by Powers and Abeare (2009), since recent economic costs were not readily available.

$$\boldsymbol{V_{ji=}} \left(\frac{\sum(\boldsymbol{C_j/E_j})}{\sum(\boldsymbol{C_i/E_i})}\right) \tag{3}$$

Here, cost, V_{ji}, is the CPUE (landings (C) / Sets (E)) of the destination grid cell (j), divided by the CPUE of the original displaced grid cell (i). This is then summed for all displaced cells to determine the overall weekly change in cost ($V = 1$ is the baseline for all average fishing effort with no movement).

Thus, if $V_{ji} = 1$, the CPUE of the displaced and destination grids must be the same. Because the distance between the displaced and destination grid is set at a maximum of 60 km, and because the direction of approach from the fisher is unknown (homeport is unknown), the costs associated with a change of position is considered negligible relative to the change in CPUE. Therefore, a value of $Vji > 1$ is indicative of an increase in cost, since it is assumed that any destination CPUE above the origin grid cell CPUE would have an expected increased socio-economic cost, otherwise the fisher would have been fishing there in the first place (Power & Abeare, 2009).

Costs in this evaluation are unit-less, and is expressed as a proportion of the normalized cost of the original fishing effort (i.e. 1). This is unit-less because it is intended to reflect that costs to displacing fishing may be financial (e.g. labour, transit, fuel), and may also include effects on social capital (e.g. business relationships, conflict between other fishermen; DFO 2004; Powers and Abeare, 2009).

3.4. Threat

To quantify the conservation effects of the different closures, a relative exposure value was calculated for each grid cell measuring the co-occurrence, or threat, of fishing gear (sets) and the number of whales (Breen et al., 2017). Threat can thus be calculated as

$$\mathbf{T}_{\boldsymbol{i}} = \boldsymbol{E}_{\boldsymbol{i}} \times \boldsymbol{W}_{\boldsymbol{i}} \qquad \textbf{(4)}$$

Where, T is the relative threat, E is the number of sets and W is the number of whales in a given grid cell (i), in the same week. The larger the value, the greater the risk of entanglement, as threat is a factor of the likelihood of whales and fishing occurring in the same area (Breen et al., 2017). Once threat for all co-occurring grid cells was calculated ($T = 0$ in grids where whales and fishing sets do no overlap), it was summed for each weekly distribution.

The change in threat between the original distribution (without any closures) and the displaced sets (after the closures) was used to determine the overall conservation efficacy of the spatio-temporal closures.

$$\boldsymbol{Tr}_{ji} = \sum \frac{Tj}{Ti} \qquad \textbf{(5)}$$

Where Tr_{ji} is the proportional change, or reduction, in threat based on the sum of threat after displacement (j) divided by the sum of threat with no closures (i).

Finally, a cost-benefit comparison between the cost approximation and the reduction in threat (the benefit) determined which closure strategy was most effective at minimizing the cost to the fishery while maximizing protection of NARWs.

Threat calculations used the 2017 NARW sightings data, however it should be noted that the DMA closures in the static plus DMA scenario were based on the 2018 NARW sightings. Therefore, the exposure results for this scenario will be underestimated, or incorrect. However, the cost analysis is accurate, thus, estimates of the results can still be made using this cost-benefit analysis.

3.5. Closure Strategies

Four closure strategies were examined and compared to address the concerns and recommendations of the sGSL snow crab fishermen: a static only closure, a static closure plus DMAs (representative of the strategy implemented for the 2018 fishing season), DMAs only where closures occur for a minimum of one sighted NARW, and DMAs only where closures occur for a minimum of three sighted NARWs.

The grid indices and coordinates of the static closure were obtained from the 2018 snow crab management measures as outlined on the DFO website, and were used for the static closure in both the static only and the static plus DMA scenarios (DFO, 2018d). Following the shortened fishing season and dates of the static closures, both strategies static exclusion zones were closed for the full 12-week season.

The coordinates of the three 2018 DMAs were not readily available, thus were individually drawn in ArcGIS Pro following the grid indices outlined on the map of the closures in the 2018 management measures notification (DFO, 2018d). The same DMA locations were used in all three scenarios that include this type of closure strategy; however, the closed grid cells differed between all three DMA scenarios. The closures for the 2018 static plus DMA strategy were obtained from DFO’s online reports of notices of closures, based on the 2018 NARW sightings, and consisted of any new or current closures that fell on any day within the 12-week focus of this study (DFO, 2018a). Using these reports, the DMA closures began in the third week of May, and continued until the end of the fishing season, resulting in a total of six weeks of DMA closures for this strategy. Meanwhile, the two different DMA only strategies used the 2017 NARW sightings to determine their respective closures, due to the 2018 sightings being unavailable at the time. Using the summed sightings data, closures were determined by closing grids that contained either a minimum of one or three whales (depending on the scenario) and closing a one grid buffer around the NARW observations (for a total of nine closed grids per NARW observation, following the 2018 DMA closure regulations). Despite the 2017 sightings data being the most complete data available, NARWs were only first recorded in the sGSL starting in the third week of June, therefore these two strategies only have 2 weeks of closures each.

As previously mentioned, the displacement model follows a one- and a multi-step process dependant on the type of closure being analyzed. The one-step process is used for the static only scenario, where the multi-step process is used for the strategies with DMAs. The one-step process runs the model with the averaged data with no closures in order to determine the impacts caused by a static closure alone with no weekly changes to the closed grid cells. In the multi-step, the closed grid indices were updated each week to reflect real-time changes in closures. However, in the case of the DMAs, this model did not account for the previous week's displaced results when modeling the displacement of the following week (i.e. using the displaced results from the previous week as the starting distribution for the current week). This decision was made since the average weekly distribution varied from week to week (different levels of effort) with no identifiers to determine individual vessels, in order to eliminate the risk of double counting or improperly representing the overall effort. Instead the static plus DMA scenario used the corresponding weekly displaced results from the static only scenario as the "original" distribution (since the static was in place at the start of the season and assumes what the averaging distribution would be as a result); the two DMA only scenarios used the average fishing distribution with no closures as the "original" distribution, since there is no static closure to impact fishing beforehand. Consequently, the dynamic modelling makes the additional assumption of starting over every week for simplicity of the model.

4. CHAPTER FOUR: RESULTS

4.1. Weekly Fishing Averages with No Closures

Only three months were examined: April, May and June, resulting in 12 weeks of data (Figures 4.1 through 4.12). Fishing activity starts within the defined static exclusion zone, near Shediac Valley, early in the season, followed by the Magdalen Shallows, forming a "U" shape around the Magdalen Islands. Following concentration on these two areas, fishing activity then expands towards the QC and NB coastlines. Although fishing effort covers a large area in the later weeks of the season due to the increase in overall activity, the highest concentrations of sets still remains central to the areas in the static exclusion zone, and towards the Magdalen Islands. The maximum number of sets per grid cell ranges between 100 and 125.

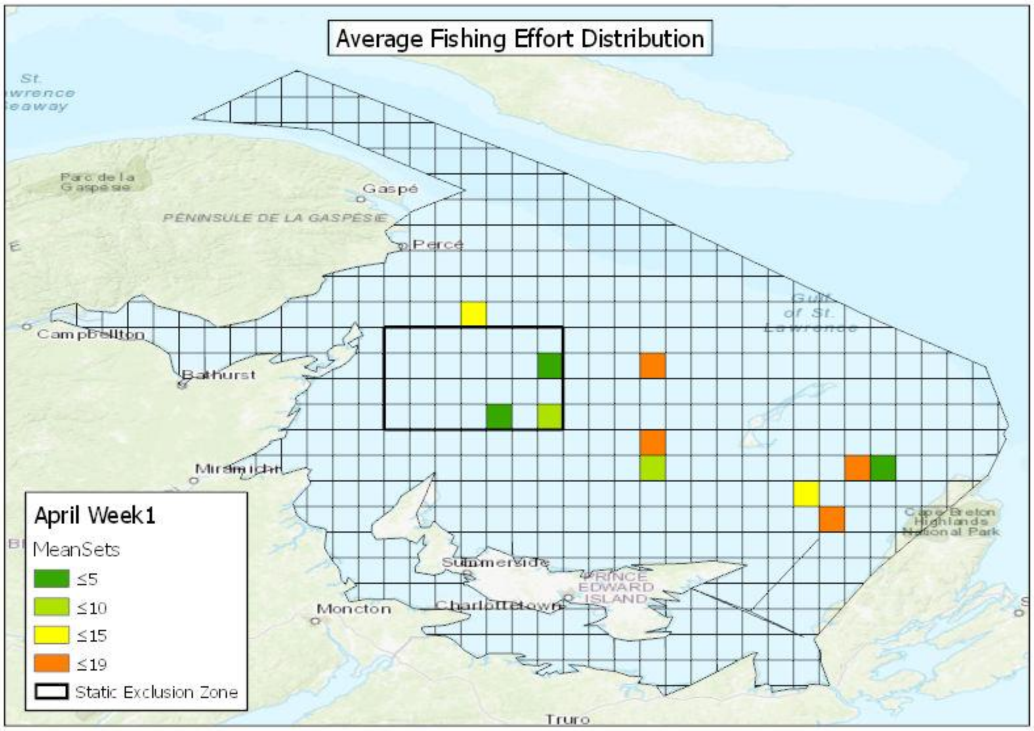


Figure 4.1 April week 1 averaged weekly fishing effort distribution (mean sets).

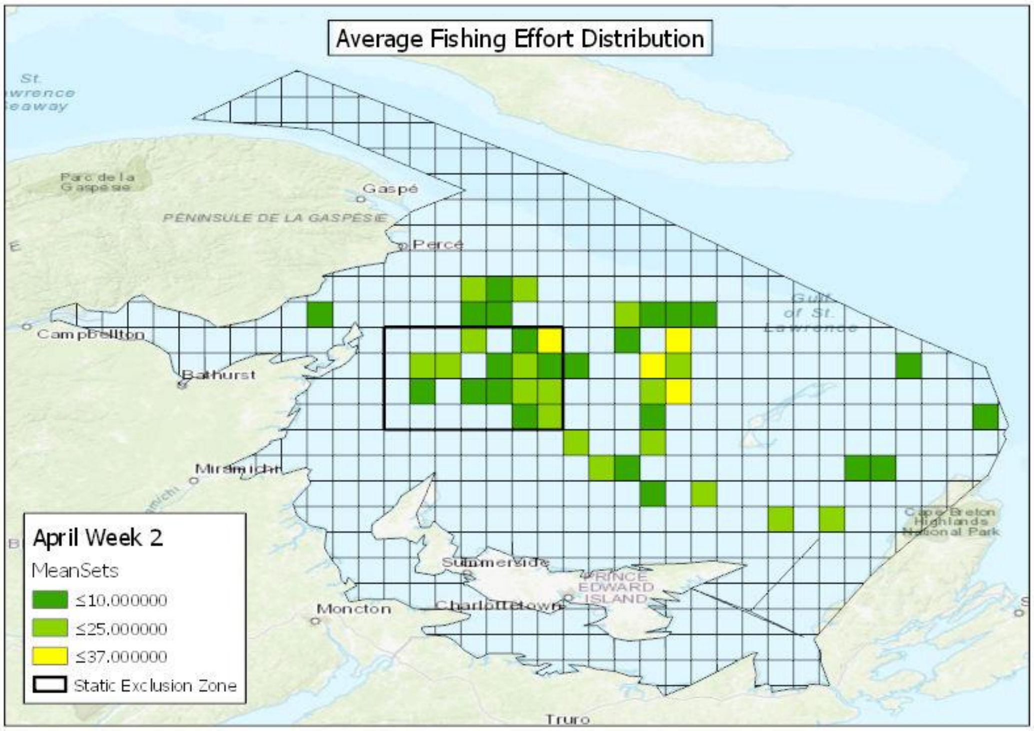


Figure 4.2 April week 2 averaged weekly fishing effort distribution (mean sets).

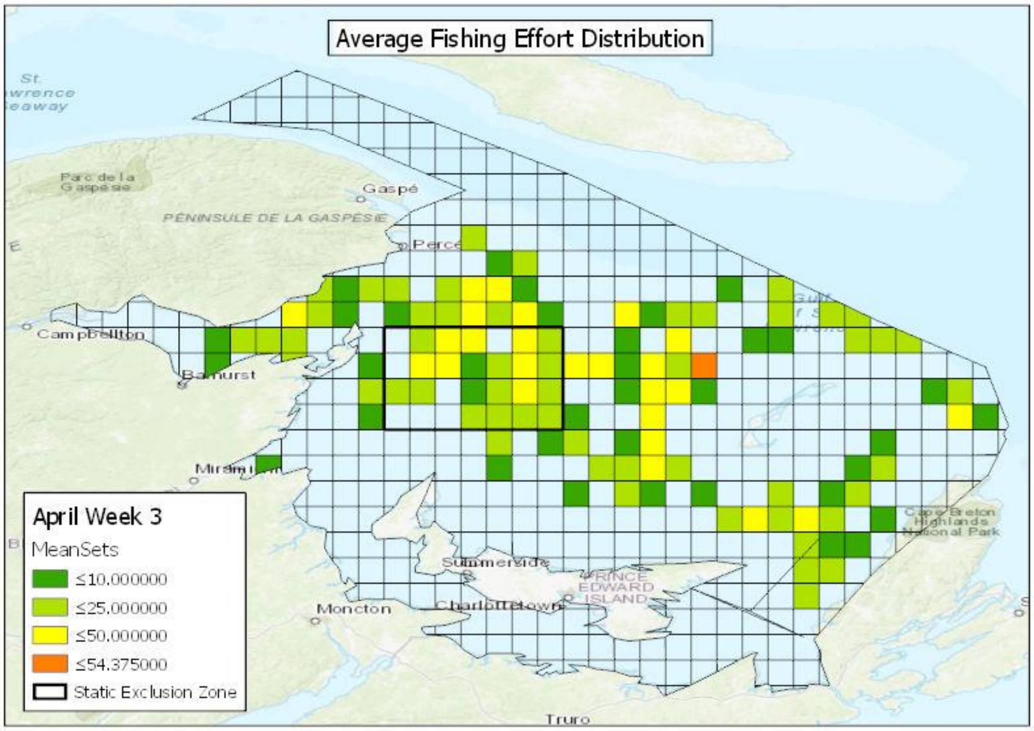


Figure 4.3 April week 3 averaged weekly fishing effort distribution (mean sets).

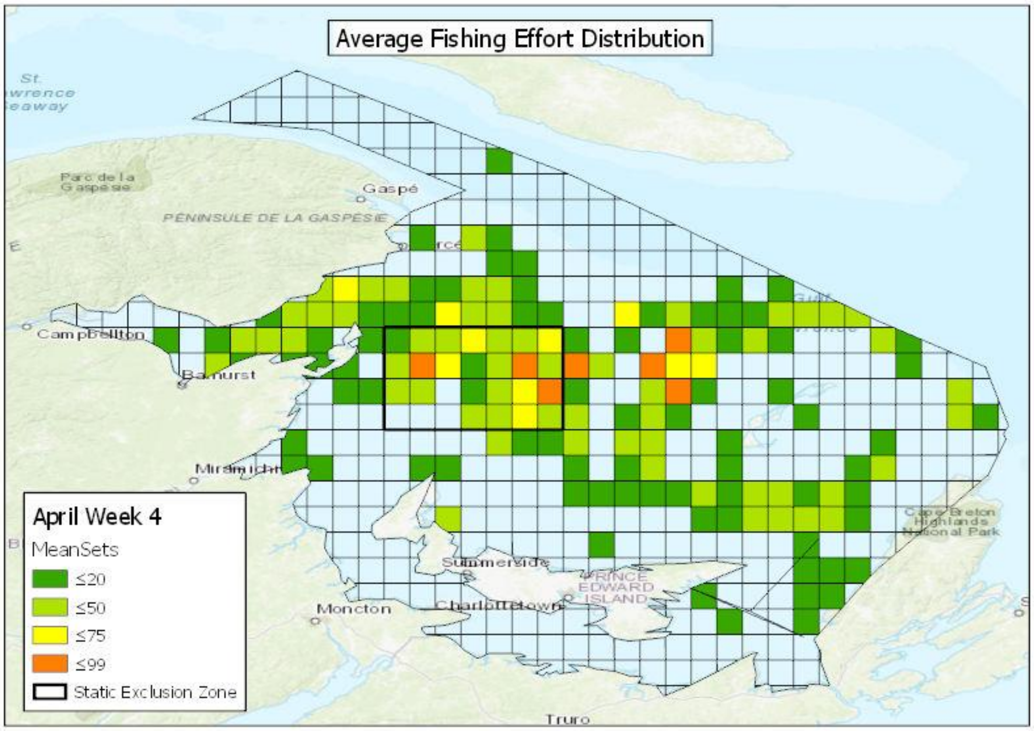


Figure 4.4 April week 4 averaged weekly fishing effort distribution (mean sets).

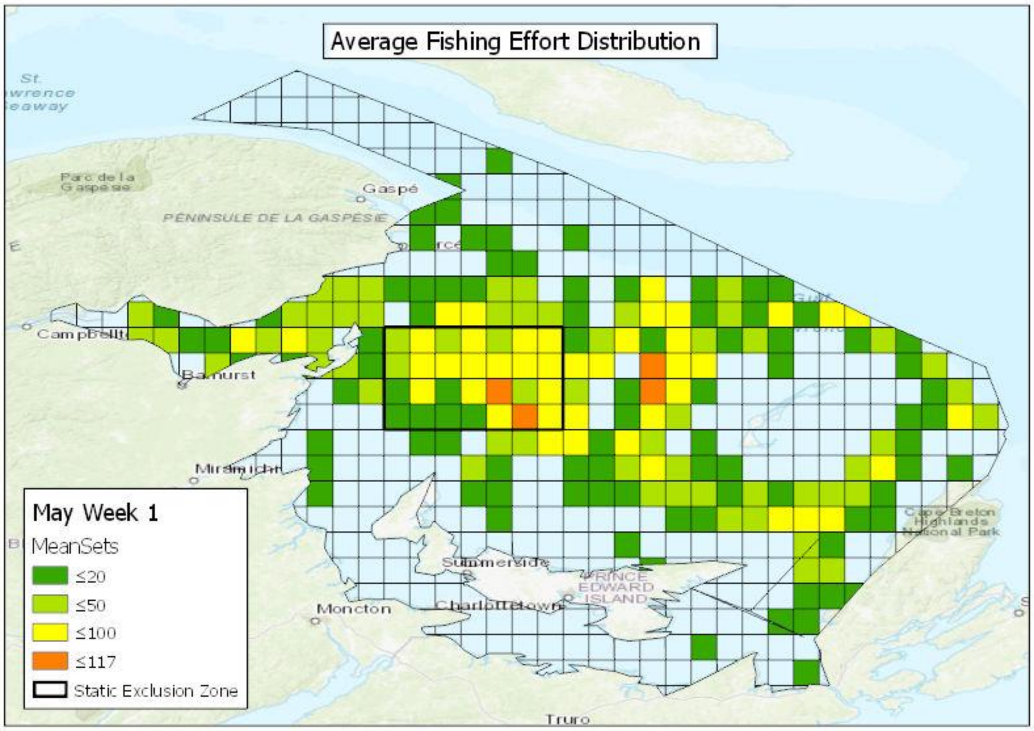


Figure 4.5 May week 1 averaged weekly fishing effort distribution (mean sets).

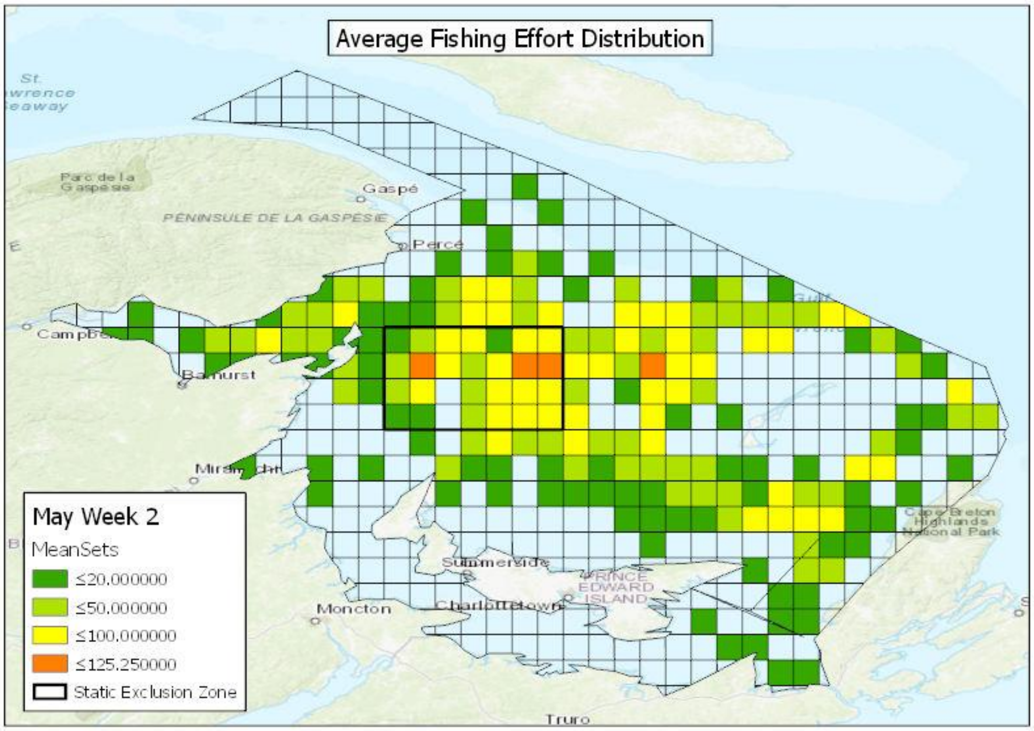


Figure 4.6 May week 2 averaged weekly fishing effort distribution (mean sets).

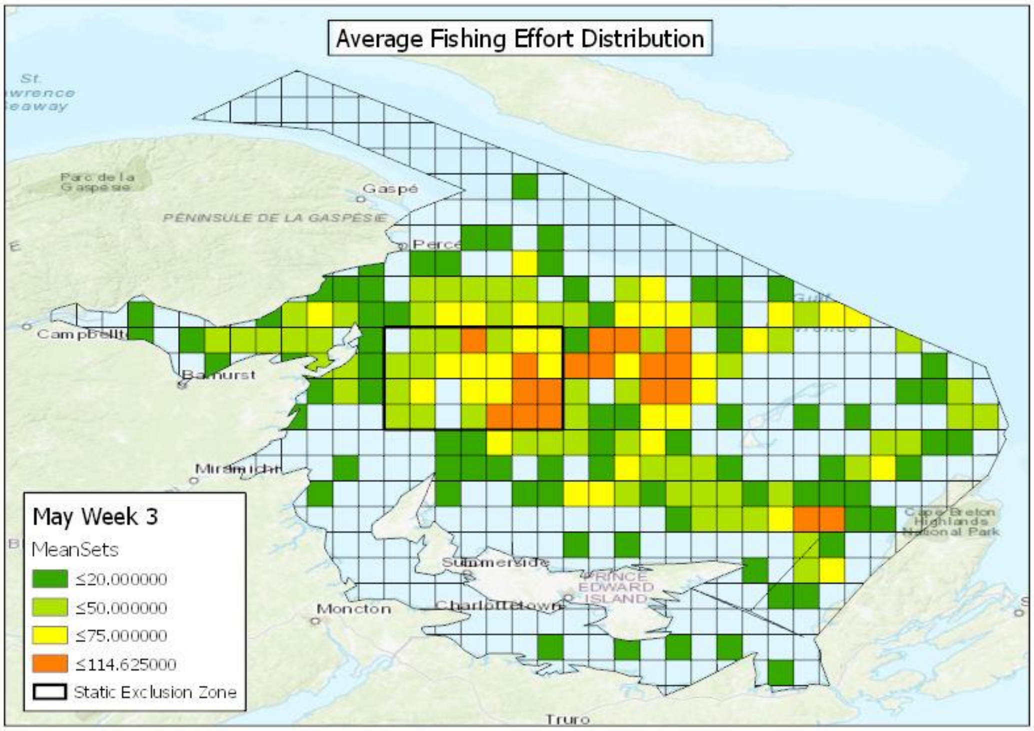


Figure 4.7 May week 3 averaged weekly fishing effort distribution (mean sets).

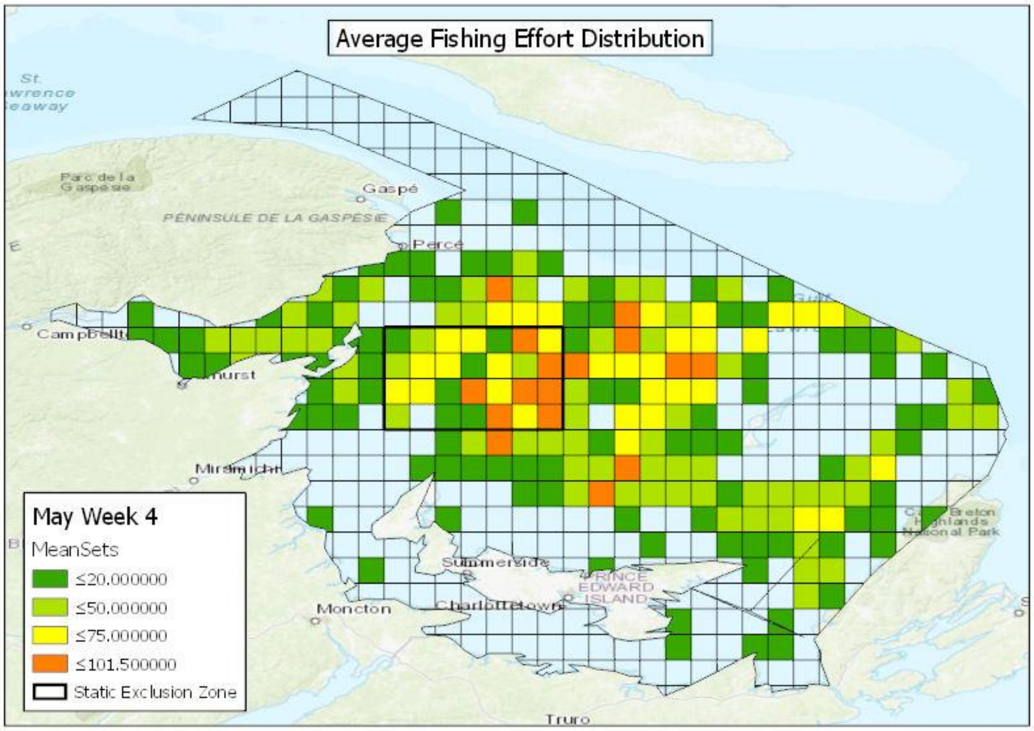


Figure 4.8 May week 4 averaged weekly fishing effort distribution (mean sets).

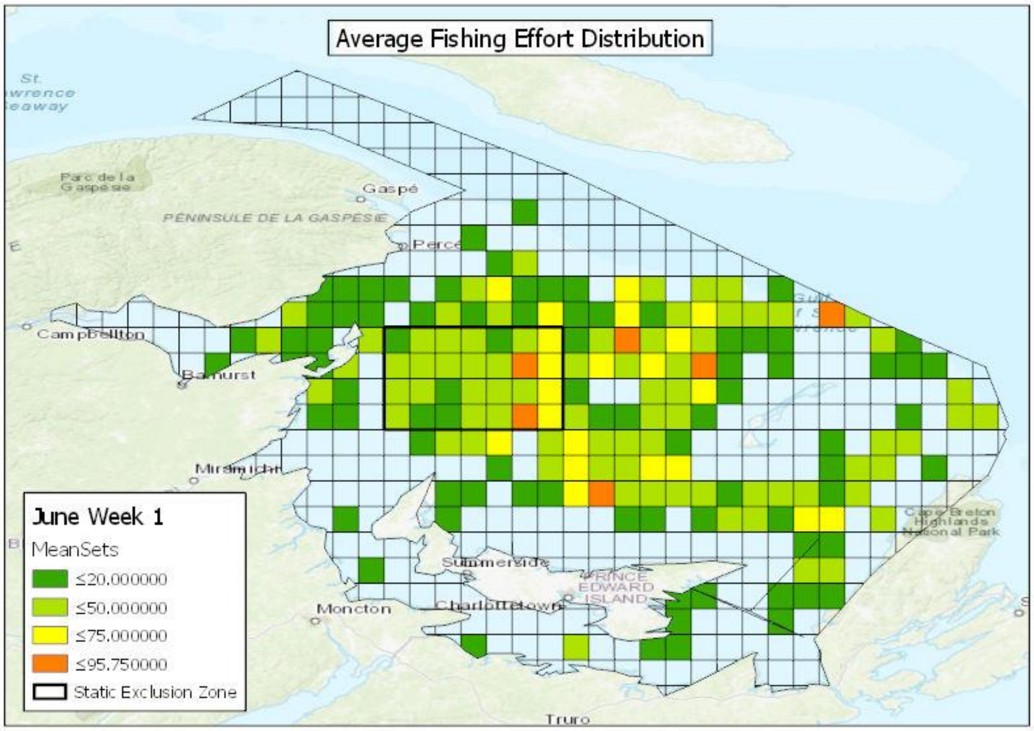


Figure 4.9 June week 1 averaged weekly fishing effort distribution (mean sets).

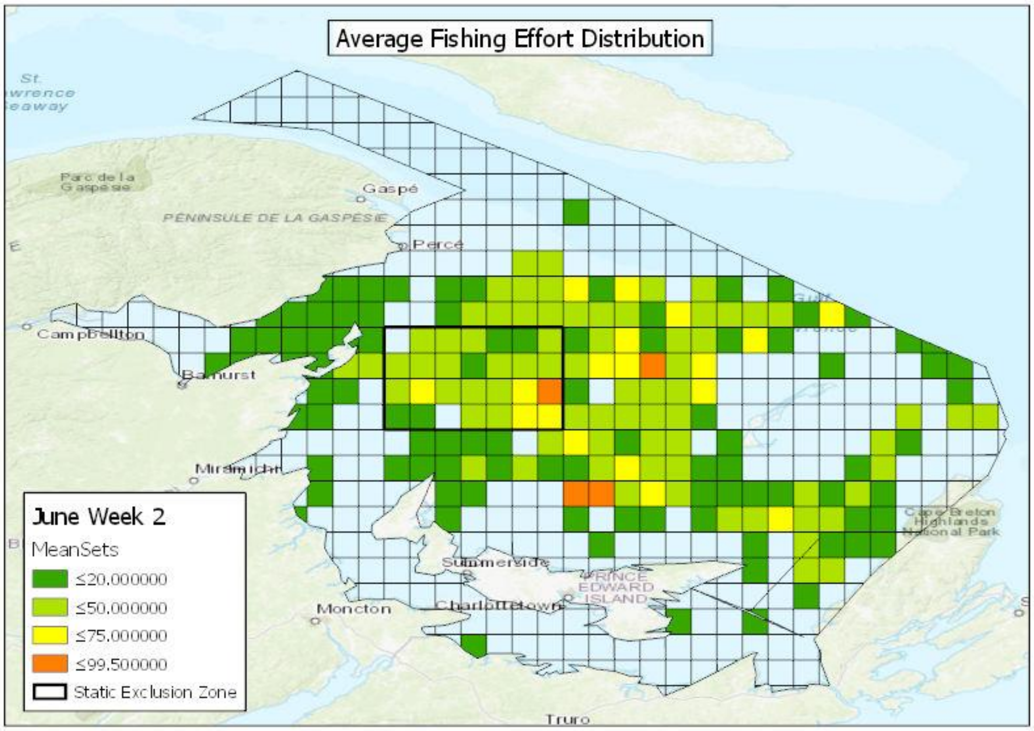


Figure 4.10 June week 2 averaged weekly fishing effort distribution (mean sets).

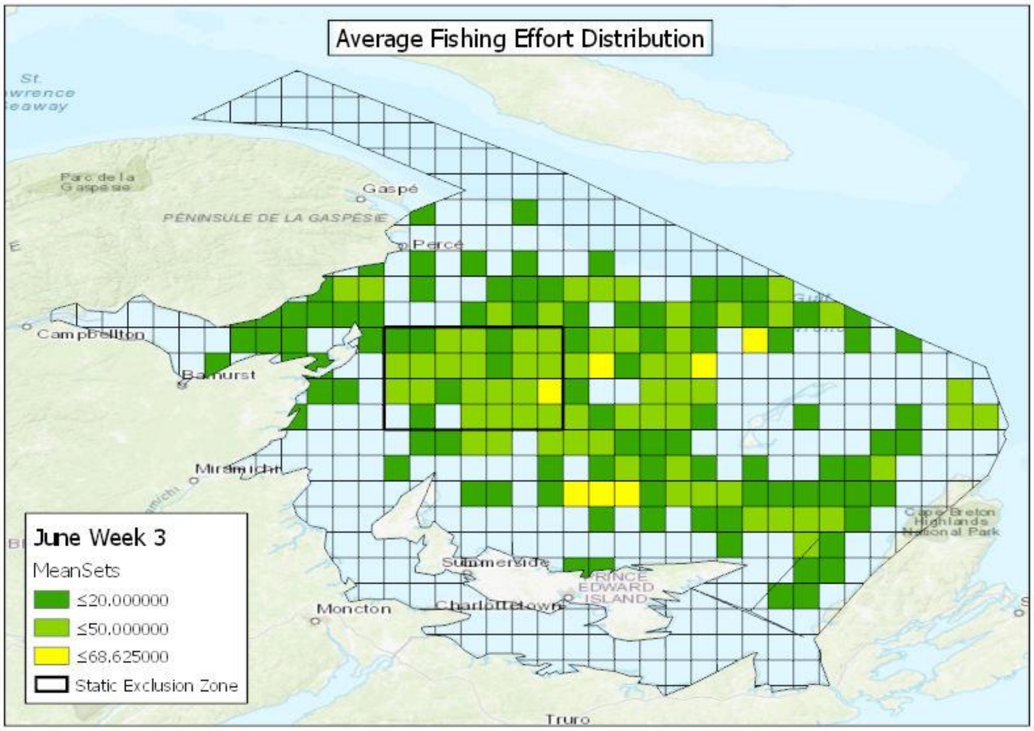


Figure 4.11 June week 3 averaged weekly fishing effort distribution (mean sets).

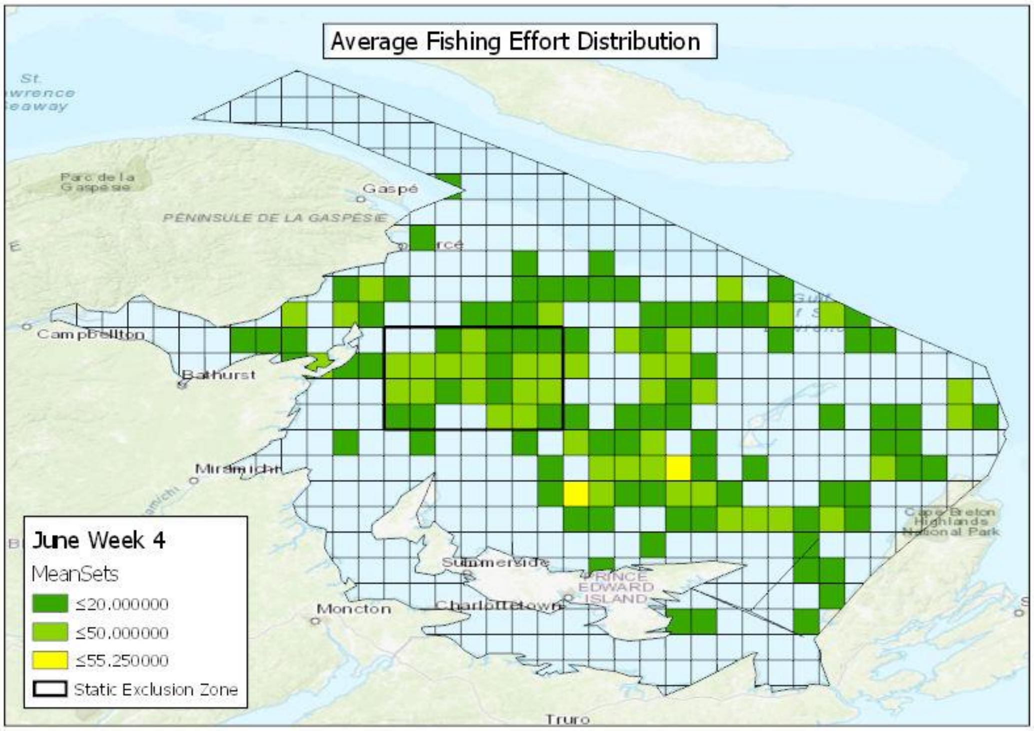


Figure 4.12 June week 4 averaged weekly fishing effort distribution (mean sets).

4.2. Weekly NARW Sightings

Based on 2017 NARW sightings data, only two weeks in the 12-week study period had recorded observations of NARW: Week 3 and 4 of June. Sightings were summarized per grid cell based on the number of whales (Figures 4.13 and 4.14). There was a large increase in the number of whales seen in week 4 versus week 3 (a maximum of 6 whales in a given grid cell in week 3 and a maximum of 30 whales in a grid cell in week 4). However, sightings in both weeks are concentrated within the static exclusion zone site, with a couple of small outliers, which is to be expected given the 2017 NARW sightings were used to determine the location of the 2018 static closure.

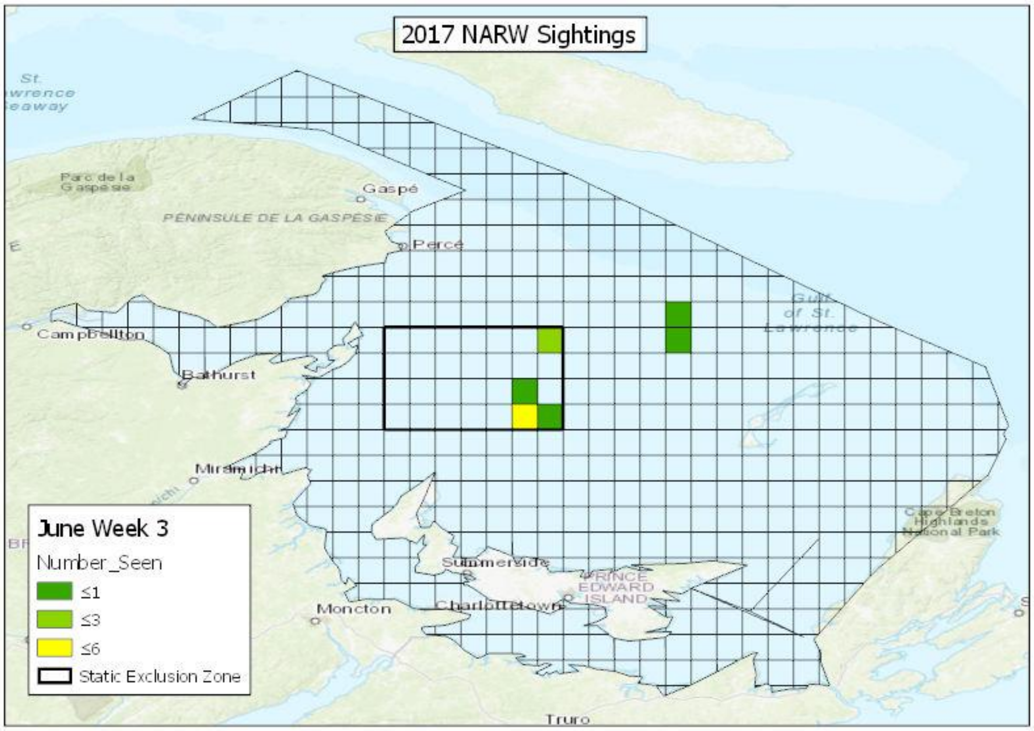


Figure 4.13 Distribution and concentration of 2017 NARW sightings for week 3 of June.

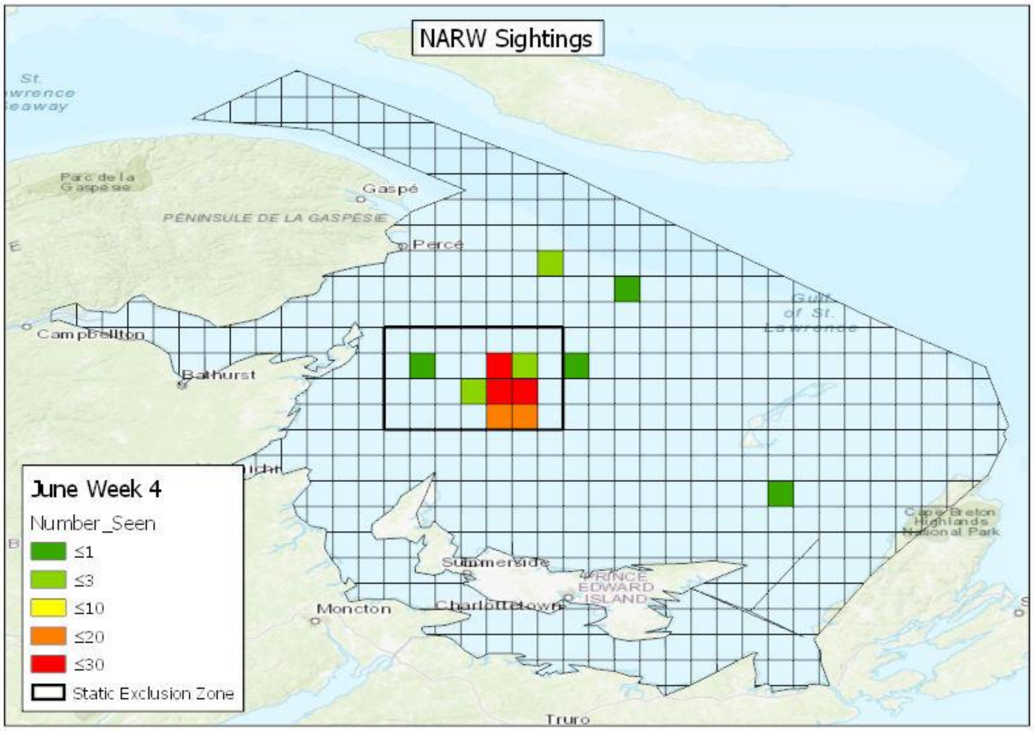


Figure 4.14 Distribution and concentration of 2017 NARW sightings for week 4 of June.

4.3. Displacement Model

4.3.1. *Static Only displacement*

The static closure encompasses 28 individual grid cells and resulted in displacement of fishing effort for all 12 weeks, however, not all weeks had 28 cells of displaced fishing (Figure 4.15). Weeks 1 and 2 of April had the lowest numbers of grid cells displaced (3 and 15, respectfully), due to the variability in those weeks being open to fishing, thus had a lower amount of fishing activity when compared to the more productive months of the fishery (Figures 4.1 through 4.12). Additionally, weeks 1 and 2 of April had one grid each removed entirely from the fishery. The remaining weeks ranged from 24-28 displaced grid cells, which were displaced to an open and available (currently fished) grid cell (Figures 4.16 through 4.27).

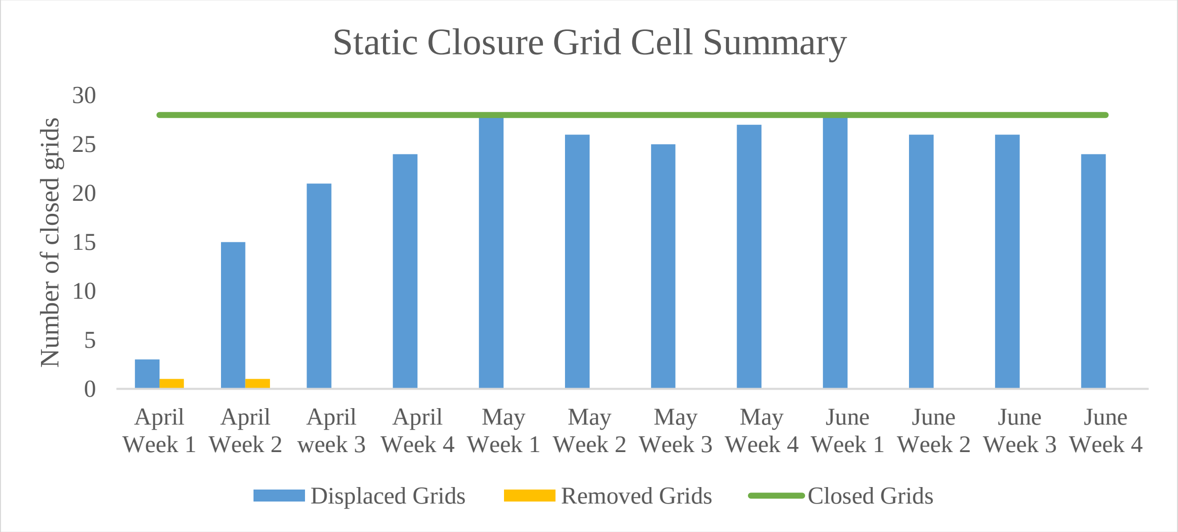


Figure 4.15 Number of grid cells impacted by the static closure; the green line represents the number of closed grid cells (n=28 for all weeks), the blue bar represents the number of grid cells displaced by the closure, and the yellow bar represents any fishing effort completely removed from the fishery.

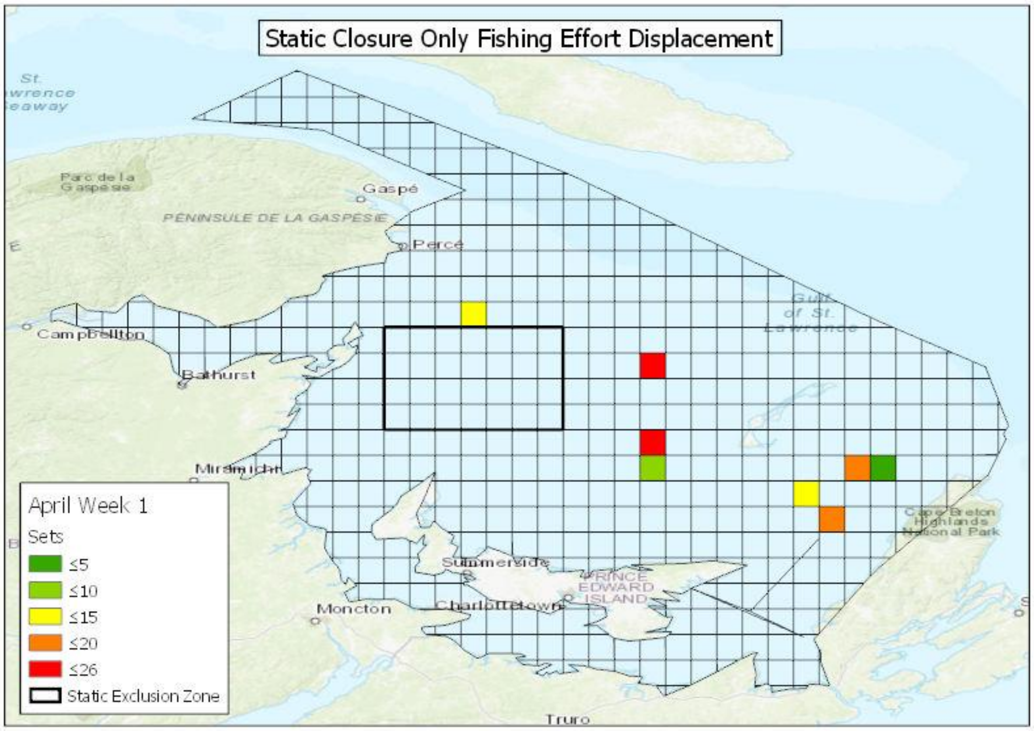


Figure 4.16 April week 1 displaced fishing effort (number of sets) from a static closure only.

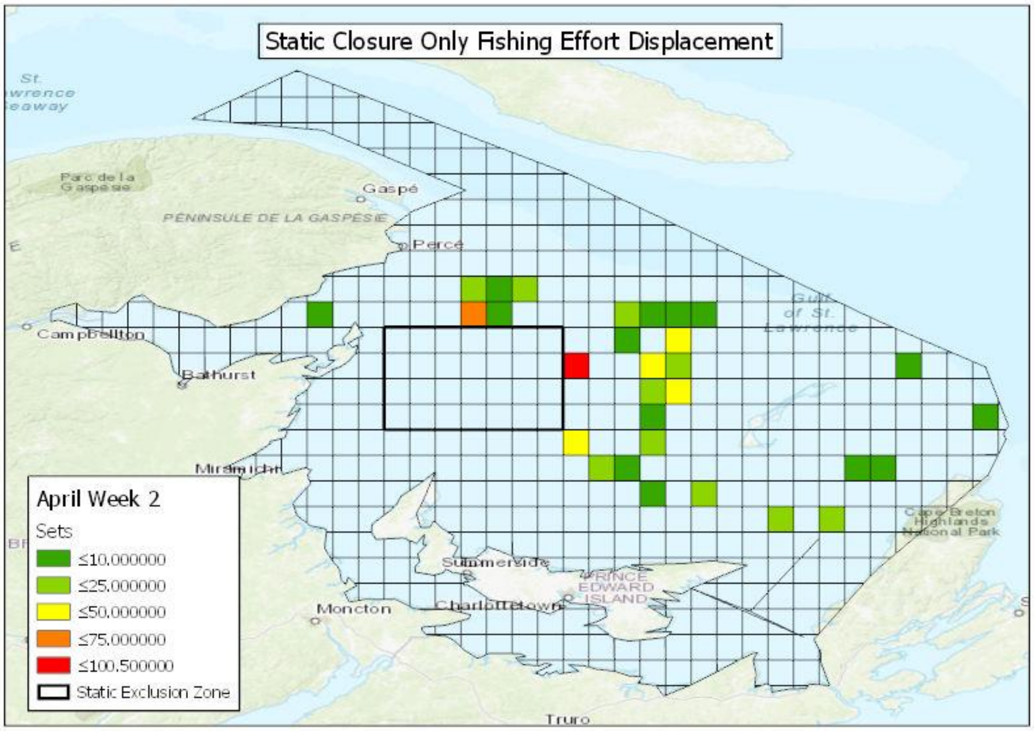


Figure 4.17 April week 2 displaced fishing effort (number of sets) from a static closure only.

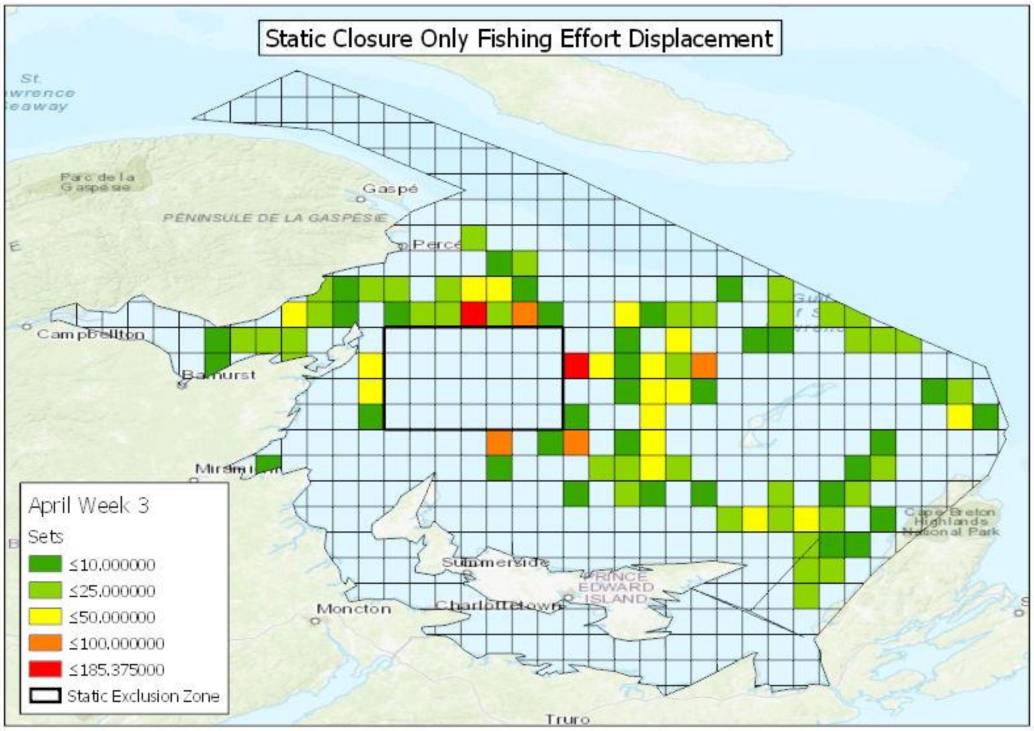


Figure 4.18 April week 3 displaced fishing effort (number of sets) from a static closure only.

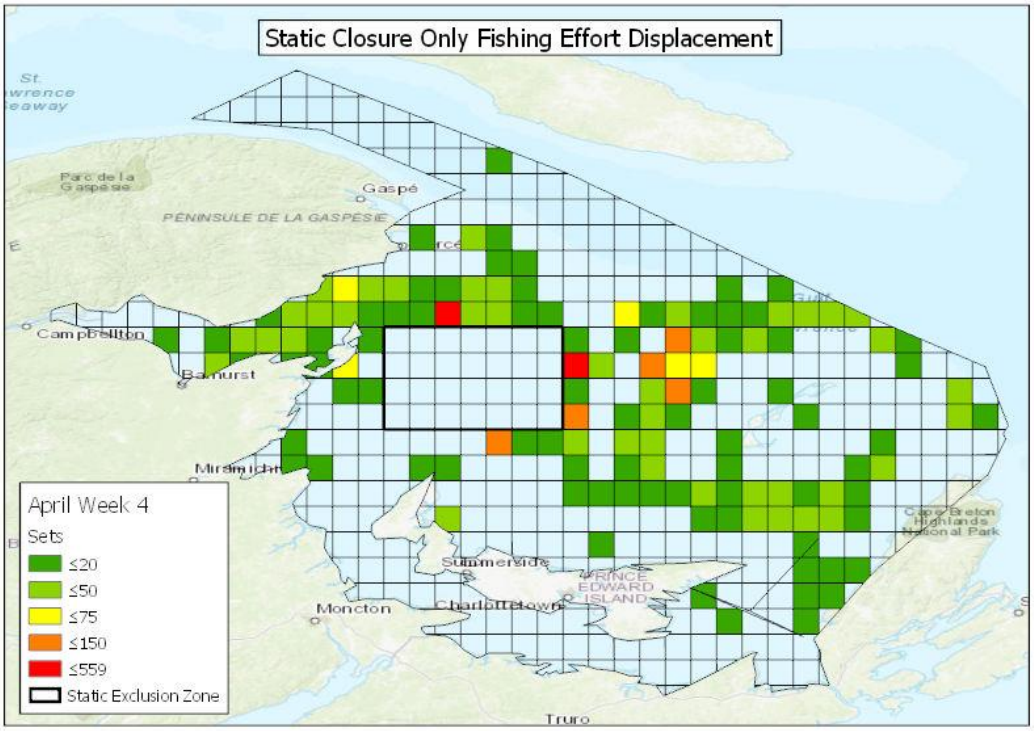


Figure 4.19 April week 4 displaced fishing effort (number of sets) from a static closure only.

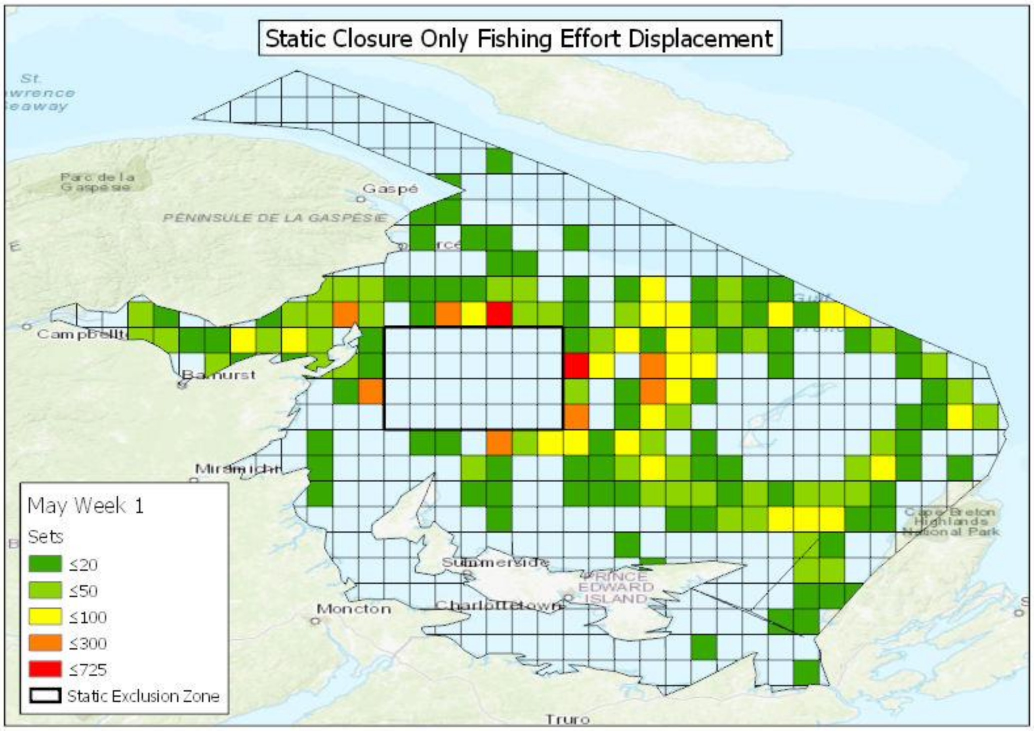


Figure 4.20 May week 1 displaced fishing effort (number of sets) from a static closure only.

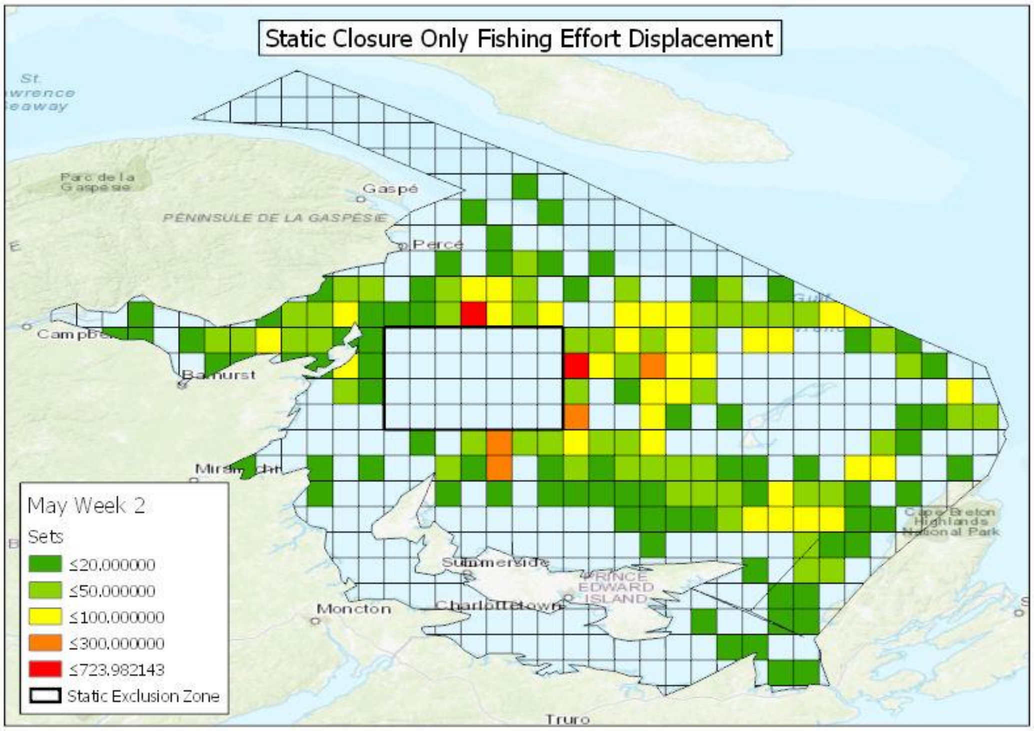


Figure 4.21 May week 2 displaced fishing effort (number of sets) from a static closure only.

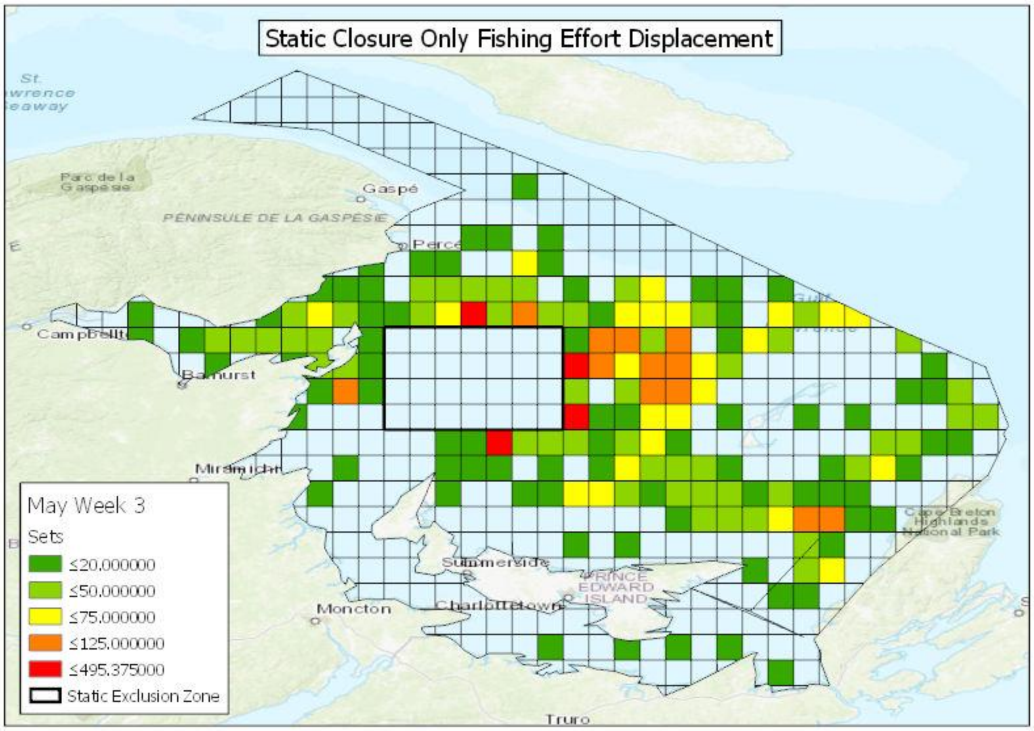


Figure 4.22 May week 3 displaced fishing effort (number of sets) from a static closure only.

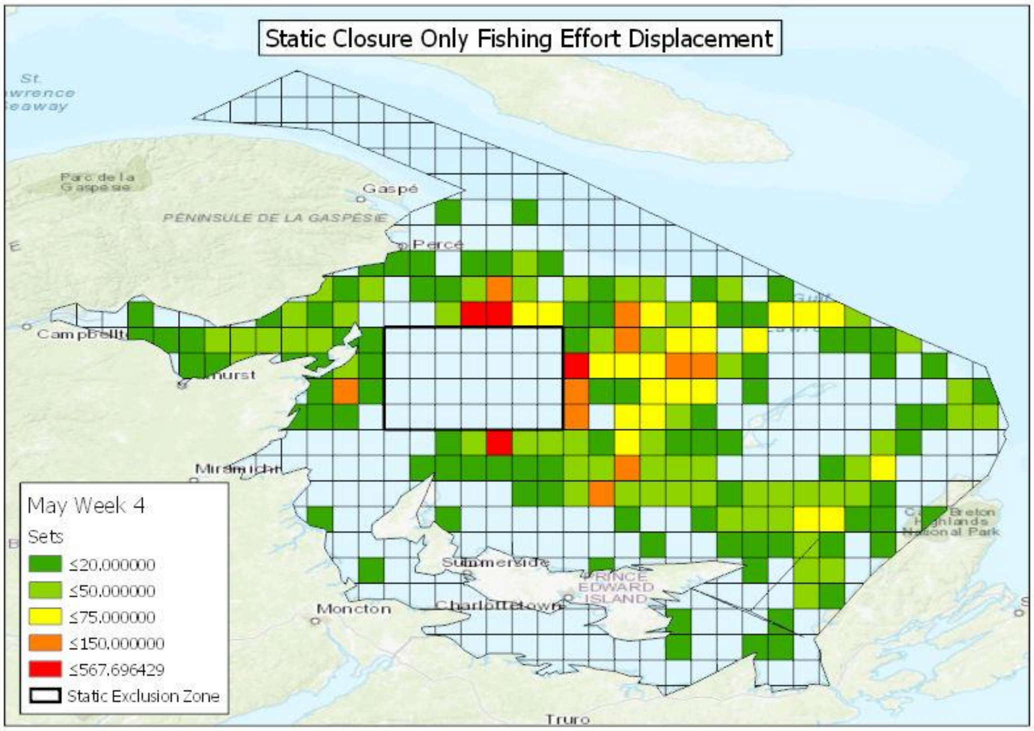


Figure 4.23 May week 4 displaced fishing effort (number of sets) from a static closure only.

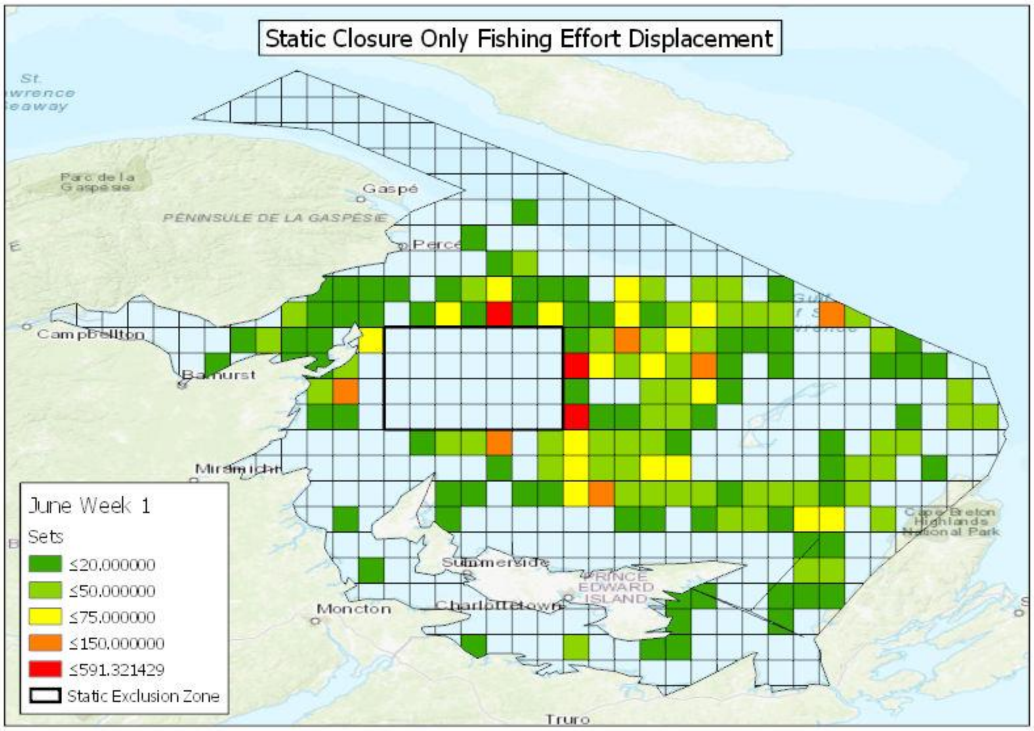


Figure 4.24 June week 1 displaced fishing effort (number of sets) from a static closure only.

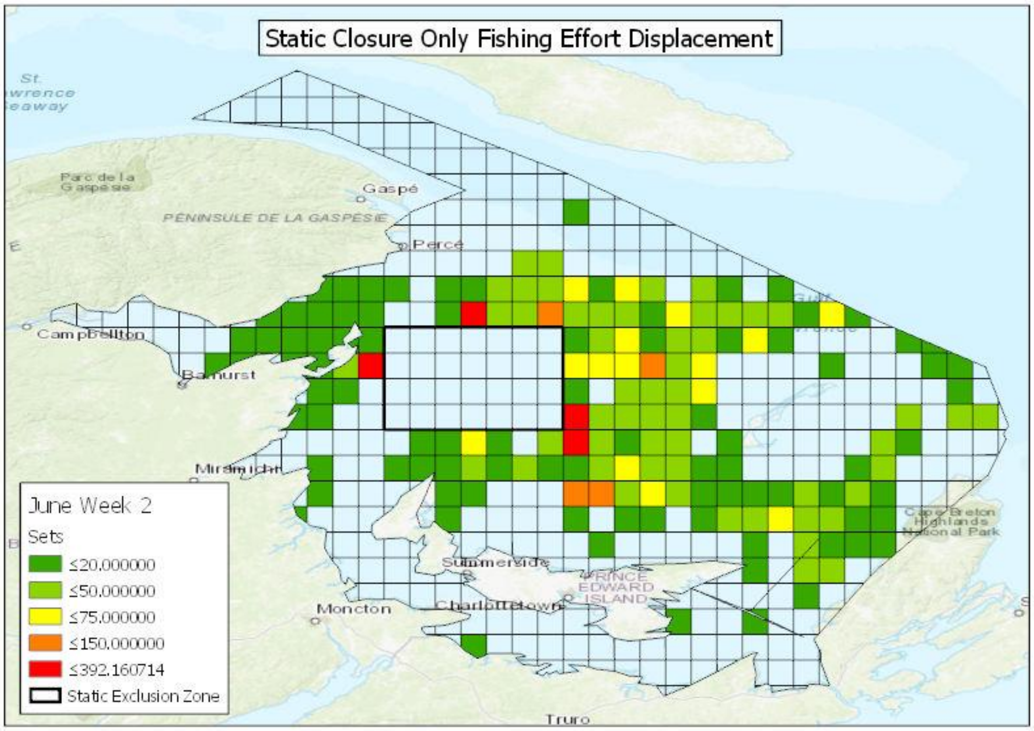


Figure 4.25 June week 2 displaced fishing effort (number of sets) from a static closure only.

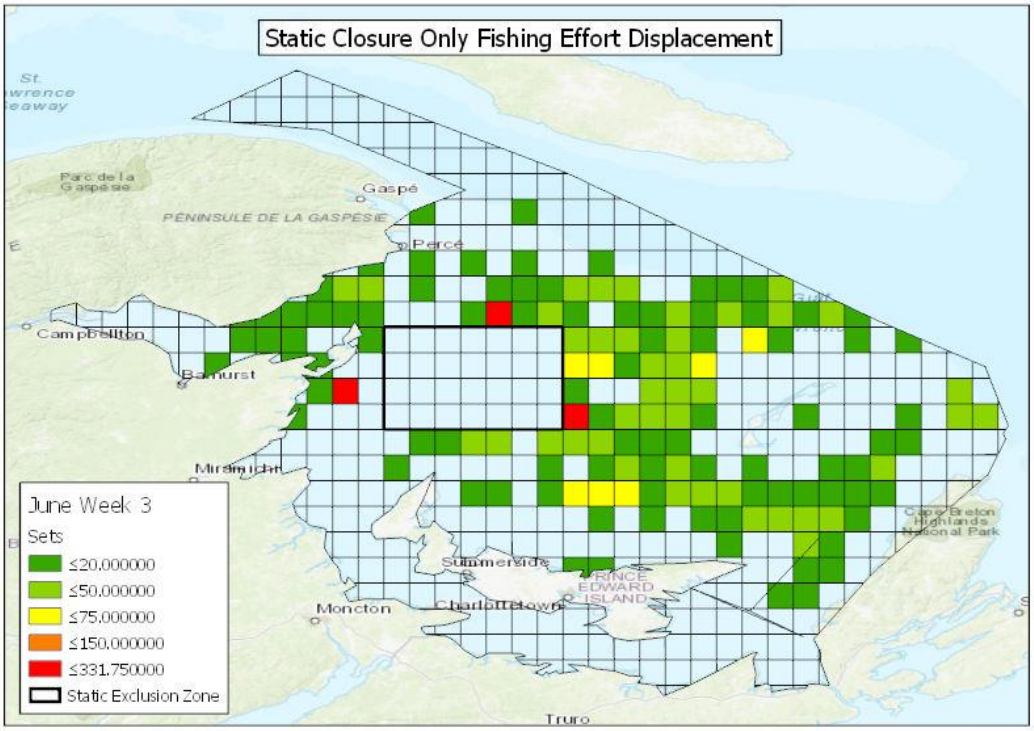


Figure 4.26 June week 3 displaced fishing effort (number of sets) from a static closure only.

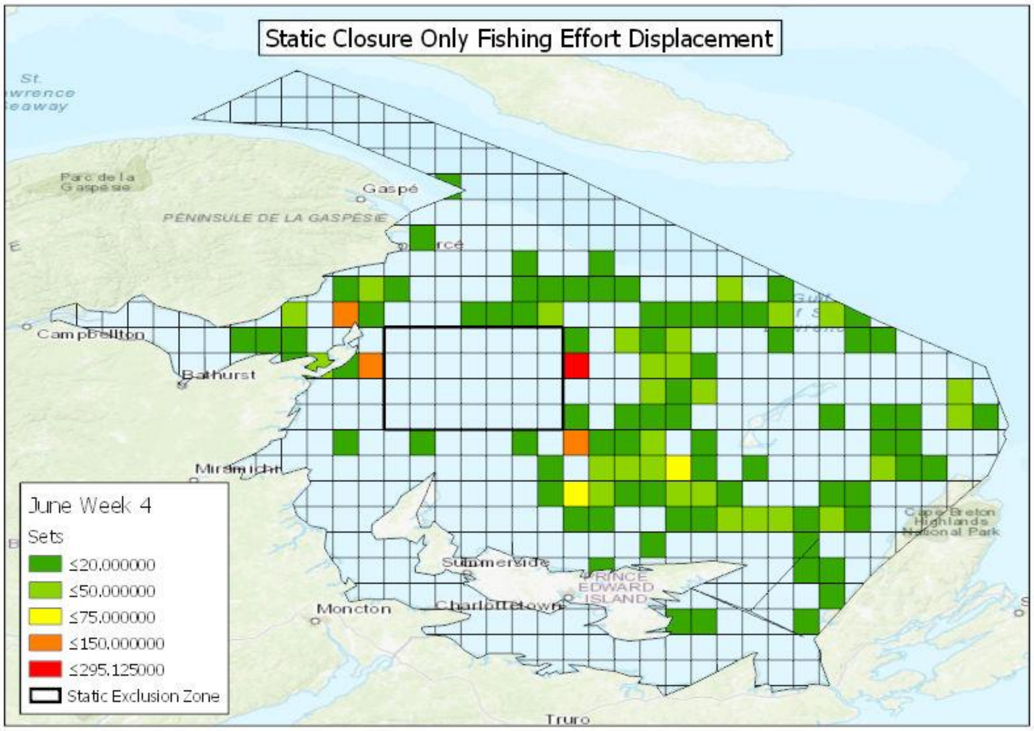


Figure 4.27 June week 4 displaced fishing effort (number of sets) from a static closure only.

The displacement distribution follows a similar pattern in each week of the season, where the displaced sets moved to a grid cell immediately adjacent to the closure area; if there was not an available location directly at the closure zone boundary, then the sets moved to the next available cell, which was within two grid cells distance away from the closure. Over the entire fishing season, only 24 unique grid cells received the displaced fishing effort, of these, five grid cells received the majority of all displaced effort: GX38, GX39, GZ42, HC39 and HB42; these grids can be found on the top left side of the static closure, as well as along the right boundary and bottom right corner of the exclusion zone (Figure 2.3). From a weekly perspective, the majority of the displacement results (i.e. 5 out of 12) moved to only seven unique grid cells (see Appendix D for full breakdown). The highest number of grid cells that the displaced fishing moved to was eight, however this only occurred once (week 1 of June). Three weeks displaced to six grid cells, and one week each moved to five, three and two recipient grid cells, respectfully; the first two weeks of April had the lowest amount of recipient grid cells (two and three), due to significantly less available locations to be able to move to. As a result, maximum sets following displacement increased significantly, with the majority of the common destination grids ranging from 300 to 725 sets per grid cell.

4.3.2. Static plus DMA displacement

Using the 2018 DMA closures, there were no dynamic closures during April or the first two weeks of May; displacement for these weeks remain unchanged from the static only closures. Thus, DMA closures first started in week 3 of May, which continued to increase in number with each subsequent week; each week included the 28 closure grids plus the changing number of dynamic closures (Figure 4.28). The first DMA closures started at six closed grids, resulting in a total of 34 closed grid cells in week 3 of May, which increased each week to a maximum of 61 closed grids during the final week of the season (June week 4), with a total of 33 dynamic grid closures. Despite the large number of closed grids, a much smaller proportion of grid cells were actually affected by the closures. The highest number of grid cells impacted by the DMA closures (not including the static closure impacts) was 15 which occurred in week 1 of June, which had 22 DMA grid closures; week 3 of June saw 14 displaced grids, followed by 12 in each week 2 and 4 of June. May saw the least amount of displaced DMA grids with six (out of six closures) and 11 (out of 17 closures), for weeks 3 and 4 respectfully, which is to expected based on the amount of fishing activity and whale sightings compared to June.

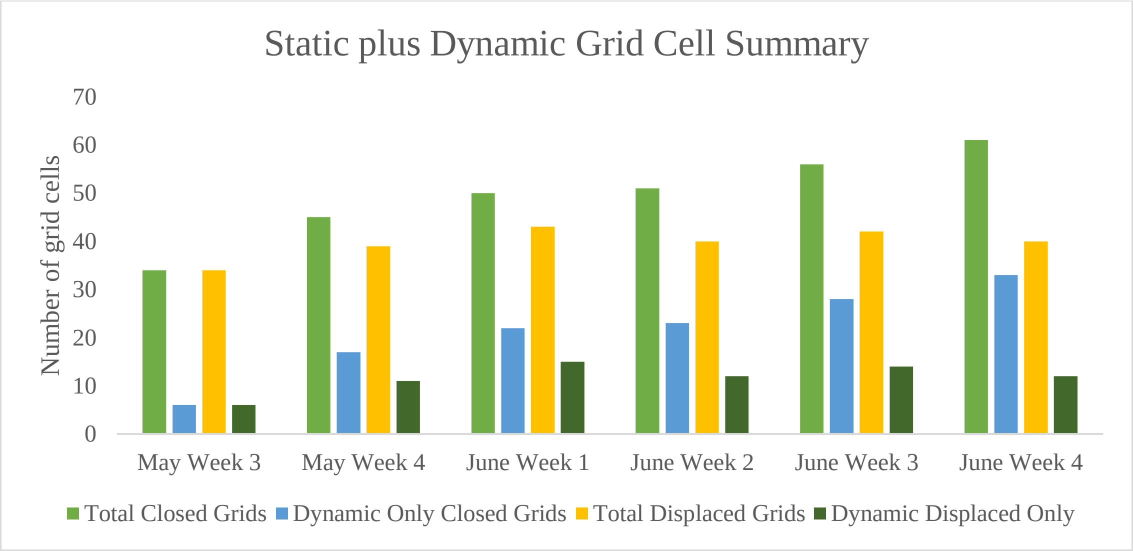


Figure 4.28 Number of grid cells impacted by the static plus DMA closures; light green represents the total number of closed grid cells (including the static closure), blue represents the number of grid cells closed in the DMAs only, yellow represents the total number of displaced grid cells (including the static displacement), and dark green represents the number of grids displaced by the DMA closures only.

Each week resulted in displacement of all impacted grid cells with no removed fishing (Figures 4.29 through 4.34). All DMA closures were exclusively found along the top end of the static closure. They started towards the centre and right side of the exclusion zone, before expanding up and to the left towards the coastline of QC. The same grids remained closed for the entirety of the fishing season, with the exception of a small weekly opening of three grids along the top right of the static closure in week 3 of June; these grids were subsequently closed the following week.

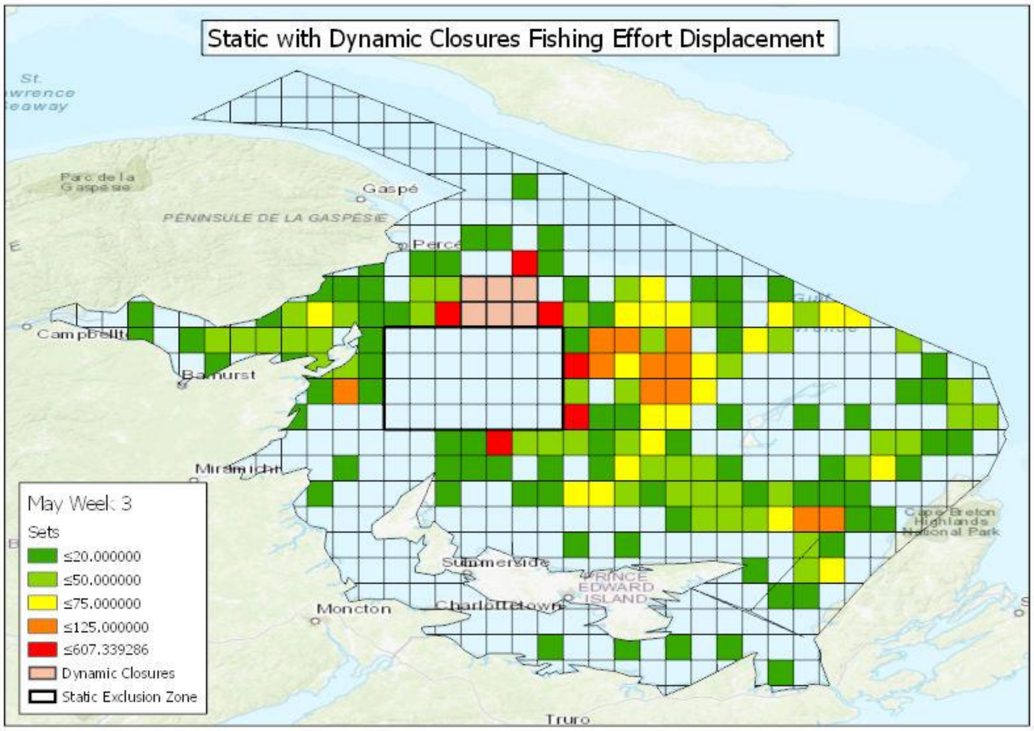


Figure 4.29 May week 3 displaced fishing effort (number of sets) from a static plus DMA closures.

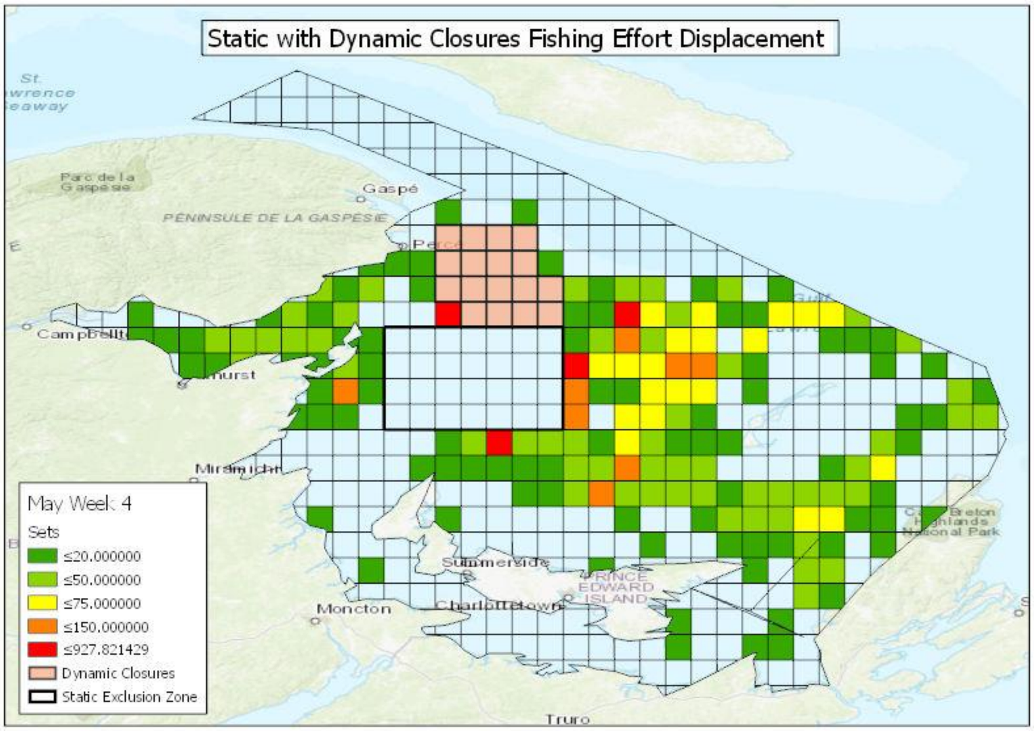


Figure 4.30 May week 4 displaced fishing effort (number of sets) from a static plus DMA closures.

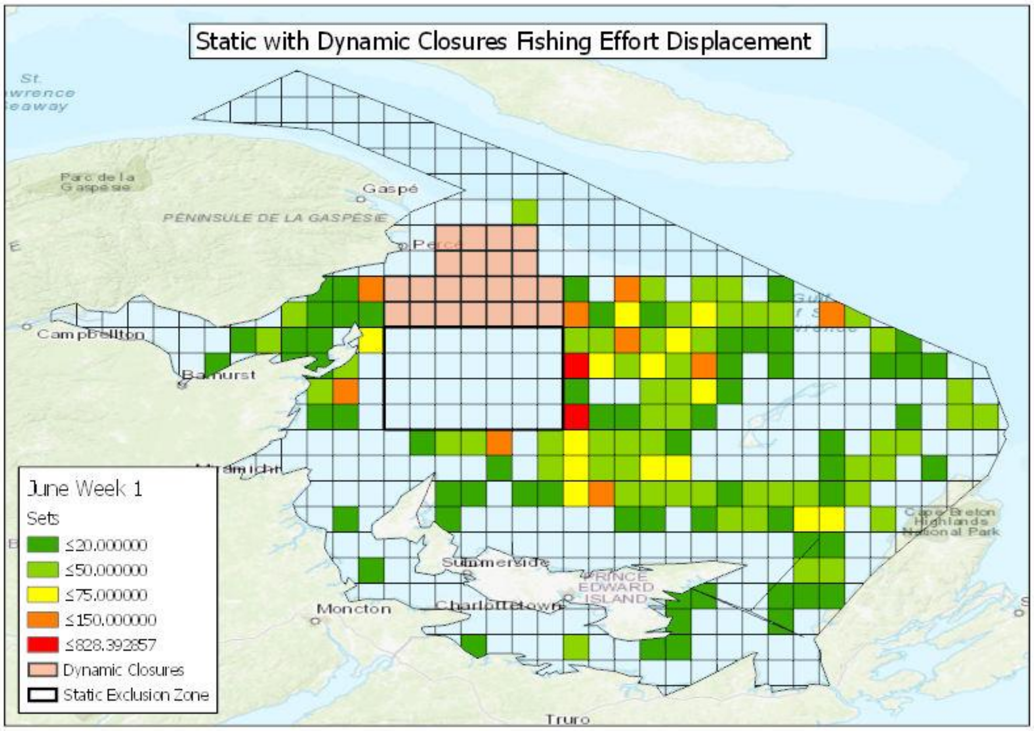


Figure 4.31 June week 1 displaced fishing effort (number of sets) from a static plus DMA closures.

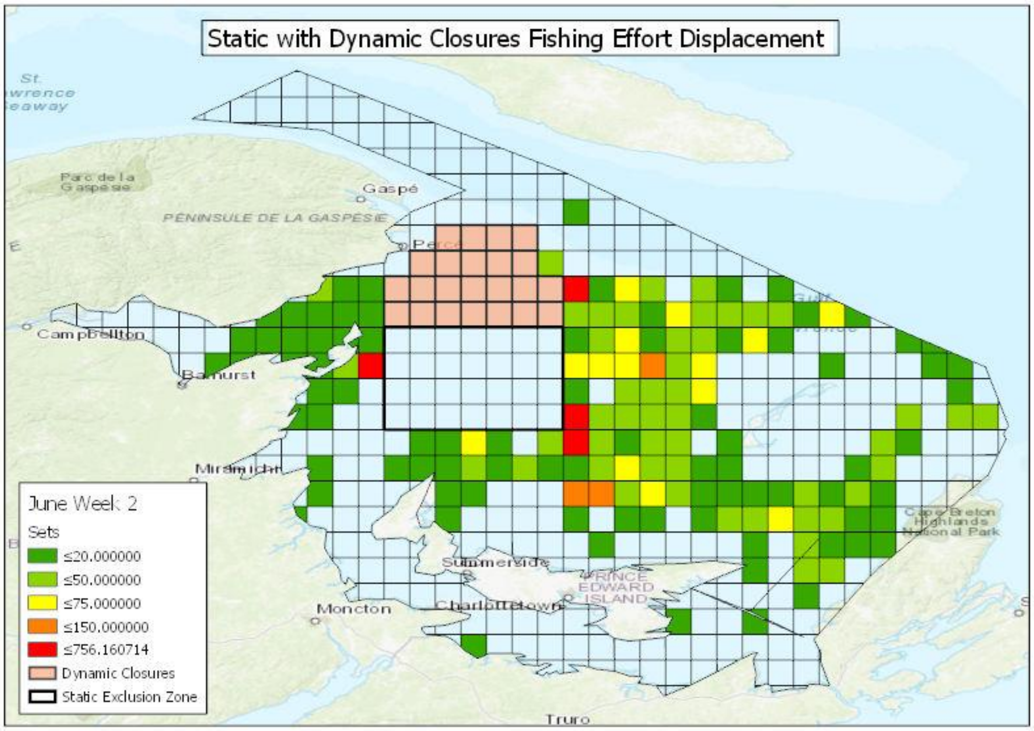


Figure 4.32 June week 2 displaced fishing effort (number of sets) from a static plus DMA closures.

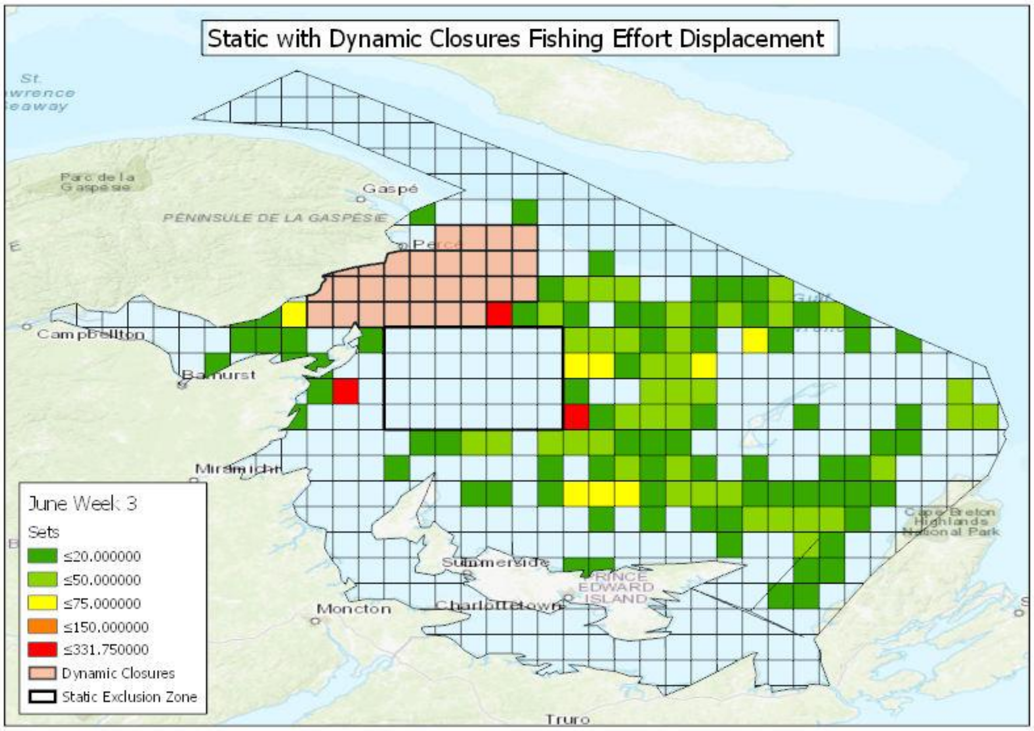


Figure 4.33 June week 3 displaced fishing effort (number of sets) from a static plus DMA closures.

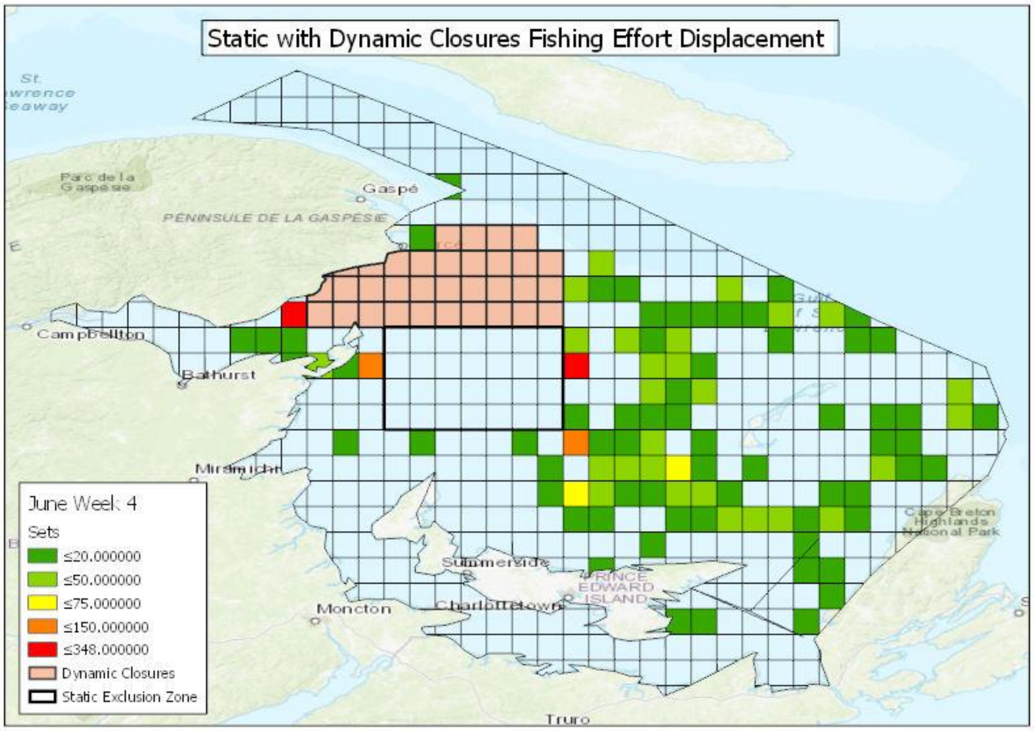


Figure 4.34 June week 4 displaced fishing effort (number of sets) from a static plus DMA closures.

The same displacement trends can be seen with these DMA closures as with the static only closures, where the displaced grids moved to the boundary grids of the closed areas. They also concentrated around the same area as the static only results, and moved to the same grid cells between weeks, regardless of the DMA closures. As such, over the six weeks of DMA closures in the season, all displaced fishing effort moved to only 17 unique grid cells, in which GW42, GX31, GX37, GX39 and GZ42 had the highest proportion of displaced effort. Examining displacement from a weekly perspective shows that the majority of displacement results (i.e. three) only moved to three new grid cells (see Appendix D for full breakdown). Week 1 of June again had the highest number of recipient grids with six, followed by week 4 of June with five. Finally, week 4 of May had the lowest amount of recipient grids, with only two cells receiving all activity from the 11 displaced grid cells. Moreover, the maximum number of sets per destination grid cell also increased, as with the static only scenario to a range between 300 and 927 sets per grid cell in the most heavily chosen cells.

4.3.3. DMA only displacement

The dynamic only scenarios used the 2017 NARW sightings to determine which grid cells would be closed every week. Since there are only NARW sightings starting in week 3 of June for this dataset, only week 3 and week 4 of June were used in the analysis. Scenarios for the DMA only strategies were closures for a minimum of one NARW sighted and for a minimum of three NARWs sighted, resulting in four weekly outcomes. Since there were more sightings in week 4 compared to week 3, there were more closures in week 4 for both scenarios; additionally, since the first scenario created closures based on one NARW sighting, the weeks of these closure had more impacted cells than the three NARW sightings situation (Figure 4.35). Consequently, week 3 of the one NARW DMA closures had more closed grid cells than week 4 of the three NARW DMA scenario (34 and 31, respectfully). Week 4 of the one NARW scenario had double the number of closed grids compared to the three NARW DMA with 63 closures versus 31. As with the static plus DMA scenario, less grid cells were impacted and displaced compared to the total number of closed grid cells in week 4 of both scenarios: despite having 63 closures in week 4 of the one NARW scenario, only 37 of those were displaced by the closures; in the three NARW scenario 22 of the 31 closed grids were displaced. Meanwhile, in week 3 of both scenarios almost all closed grids were also displaced, with 31 out of 34 and 18 out of 19 for the one and three NARW scenarios, respectfully. However, all displaced cells in the DMA only scenarios were less than the total number of displaced cells in the static plus DMA scenario (minimum of 39), but more than the static only (maximum of 28). During this week, the three NARW scenario only differed by 12 grids, which were closed due to two individual whales in the one NARW scenario. These grid cells were located slightly left to the Magdalen Island; the grid cells that were closed in both DMAs scenarios are found within the same region as the static closure. As a result, fishing effort from this location moved to the exact same grids in both situations (see Appendix D for full breakdown).

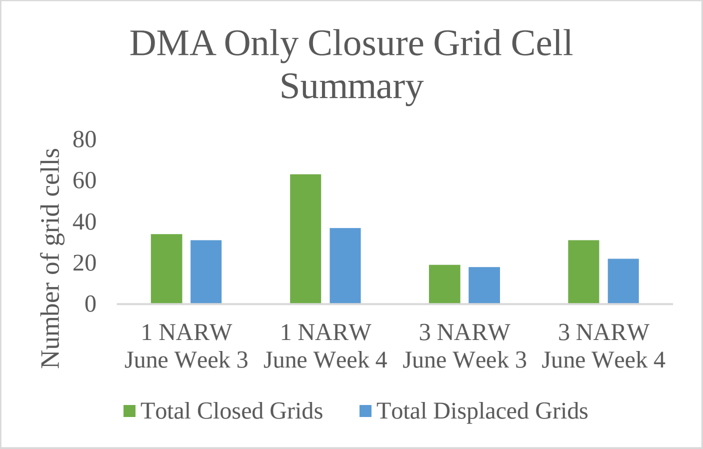


Figure 4.35 Number of grid cells impacted by two different DMA only closures; green represents the total number of closed grid cells, and blue represents the number of grid cells displaced by the DMA closures.

These closures primarily concentrated around the area of the static closure, as well as towards the top of the region, in the same manner as the dynamic closures from the static plus DMA scenario, as stated above. There was a large concentration of NARW sightings in the static closure area which is closed in the three NARW scenario, but compared to the one NARW sighted closures, several areas are not closed, thus have a higher degree of NARWs not protected by the closures compared to both scenarios in week 3. All fishing effort was displaced in both scenarios and for both weeks; no fishing effort was removed (Figures 4.36 to 4.39).

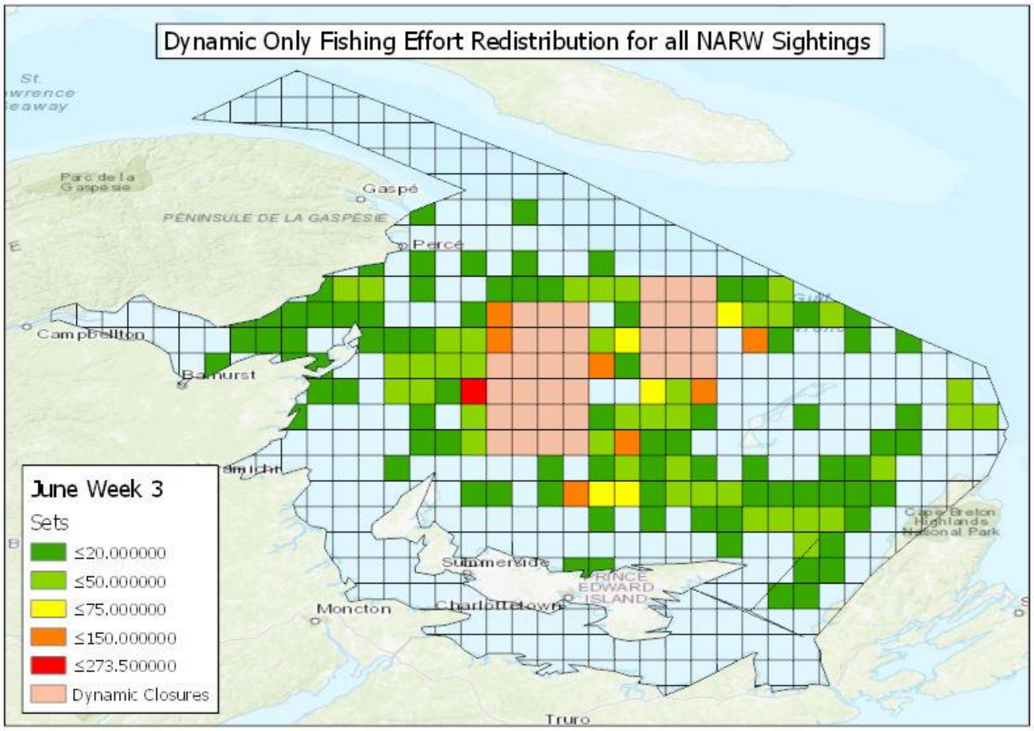


Figure 4.36 June week 3 displaced fishing effort (number of sets) from one NARW DMA closures.

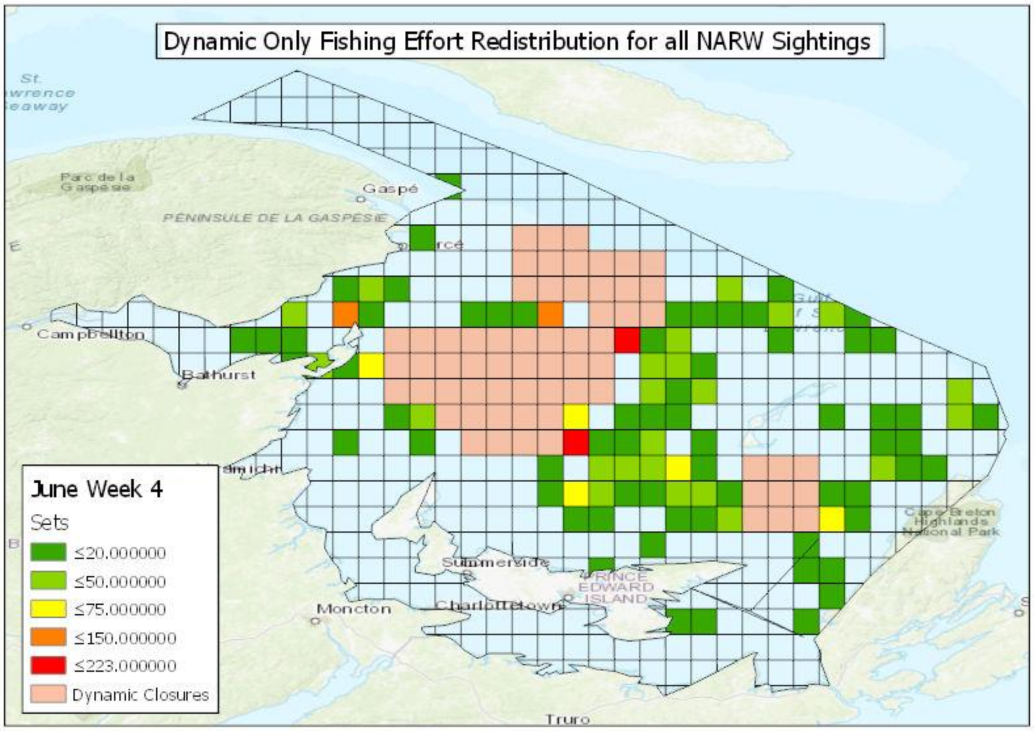


Figure 4.37 June week 4 displaced fishing effort (number of sets) from one NARW DMA closures.

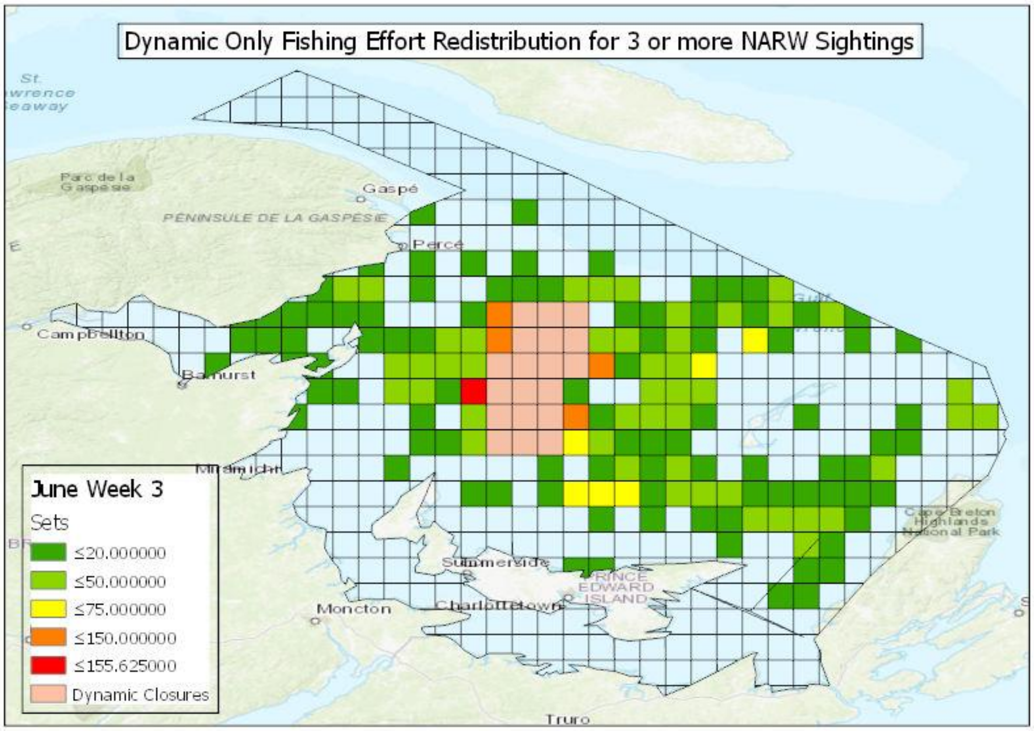


Figure 4.38 June week 3 displaced fishing effort (number of sets) from three NARW DMA closures.

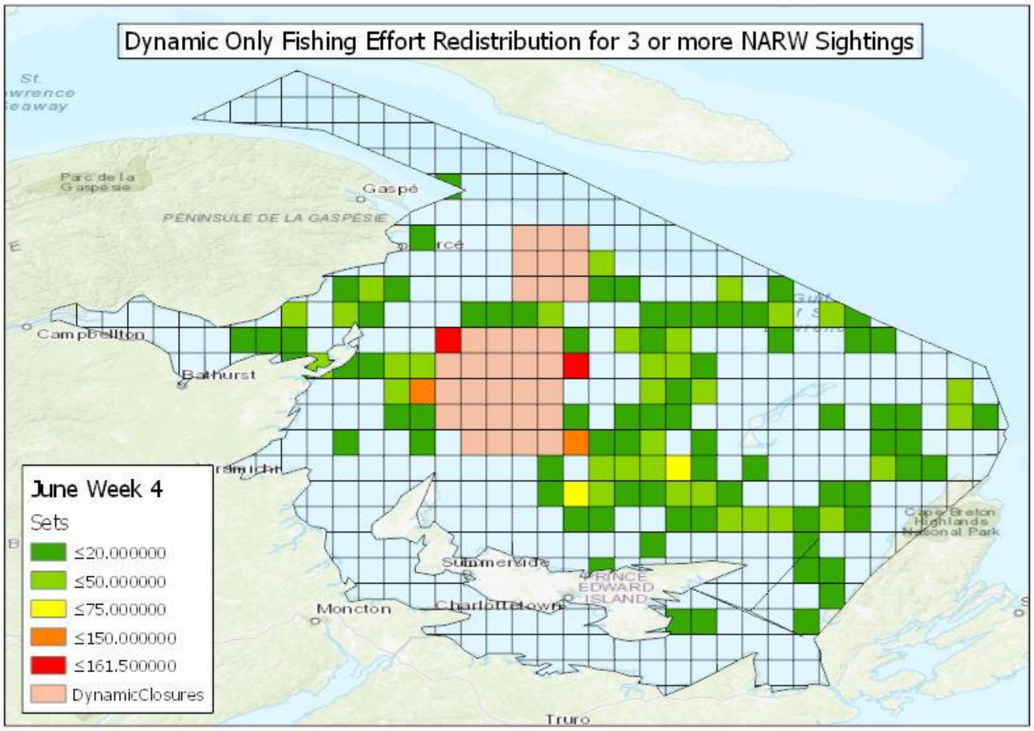


Figure 4.39 June week 4 displaced fishing effort (number of sets) from three NARW DMA closures.

The displacement trends with the DMA only closures are slightly different when compared to the previous closure types, in which the DMA only scenarios had a higher proportion of overall destination grids (i.e. 27, and includes results from both the one and three NARW scenarios). The overall proportions are of number of grid cells received per destination grid are smaller compared to the other closure types with only three grid cells receiving the majority of the displaced sets: GY44, HA38 and HC42. From a weekly perspective, week 3 of the one NARW sightings scenario differed significantly from the others in which the 31 displaced grids moved to 15 unique cells; meanwhile, week 4 of the all sightings, and week 3 of the three or more scenarios both had nine recipient grids, whereas week 4 of the three or more scenario only have seven recipient grids.

Subsequently, when further comparing the recipient grid cells for each of the closure types, four grid cells were found in common across all four closure types: GX39, GX41, GZ34, and GZ42; of these, GX39 and GZ42 were the majority choices for both the static only and static plus DMAs resulting in 68 and 37 grid cells (overall) being displaced to these two grids, respectfully. Meanwhile, another nine grid cells were found in common between at least two of the three closure types: four were found in common between the static and static plus dynamic scenarios (GX31, GX37, GY42, and HA33); three grid cells linked the static and DMA only closure types (GX33, HB42, and HC42); and, 2 grid cells were common between the static plus DMA and the DMA only closures (GV43, and GW42; see Appendix D for full breakdown). However, when comparing the number of sets in the destination grids, the maximum number of sets is much smaller than compared to the previous two strategies. The one NARW DMAs saw an increase in sets to a maximum of 273 sets and the three NARW scenario saw a maximum of 161 sets, not much more than the mean sets in the average fishing distribution with no closures.

Moreover, when compared to the locations of the 2017 NARW sightings, three NARW grids overlap with the recipient grids: GW44, from the static plus DMA scenario; GZ42, which is a recipient in all closure types; and HA38, which was one of the top three recipients for the 3 NARW DMA only scenario.

4.4. Cost Analysis

Movement cost approximation was calculated for the four different closure scenarios. For the static only closures, the first week of June had the highest cost approximation (V = 2.21) representing a 121% increase in normal operation costs (Table 4.1). Meanwhile, the fourth week of April had the lowest expected change in cost ($V = 0.56$). Following the same trend, June had the overall highest expected movement cost, and April had the lowest.

Table 4.1 Movement cost approximation (V) for the static only closures.

Month	Week 1	Week 2	Week 3	Week 4
April	1.14	1.28	1.23	0.56
May	0.98	1.38	0.88	1.50
June	2.21	1.27	1.25	1.18

In the static plus DMA closure scenario, June once again had the highest movement cost, where $V = 3.52$, or a 252% increase in costs, in week 3 (Table 4.2). Week 3 of May had the lowest expected movement cost ($V = 0.75$), followed by week 1 of June ($V = 1.18$). Overall, in this scenario June has the highest costs associated with movement due to displacement. Costs to weeks without any DMA closures in this scenario would have the same costs as the corresponding weeks in the static only scenario.

Table 4.2 Movement cost approximation (V) for the static plus DMA closures. A (-) denotes no activity, thus no net change in movement.

Month	Week 1	Week 2	Week 3	Week 4
May	-	-	0.75	1.44
June	1.18	1.53	3.52	1.69

The two different DMA only scenarios had similar results. Both week 3 of the three NARW scenario, and week 4 of the one NARW closures produced the same approximation, $V = 1.54$ or a 54% increase in expected costs. However, week 4 of the three NARW DMA closures was higher than all other weeks and scenarios of the DMA only costs ($V = 1.79$).

Table 4.3 Movement cost approximation (V) for the two different DMA closure scenarios.

Week	1 NARW DMA	3 NARW DMA
3	1.66	1.54
4	1.54	1.79

A comparison of all four scenarios highlights the differences in movement costs between the different types of closures. Since the DMA only closures were only calculated for the last two weeks of June, only the corresponding weeks 3 and 4 of June were used in the comparison for the other two closure types. As such, the comparison of all four scenarios highlights that the static, and two DMA only closures produce similar results (Figure 4.40). However, the static closure has the lowest expected cost with a $V < 1.25$, whereas in all other three scenarios $V > 1.50$. The main standout is the static plus DMA scenario, where week 3 is significantly higher than all other weeks and scenarios where $V = 3.52$, and week 4 (V= 1.69) is larger than all other week 4 costs, except the three NARW DMA only scenario.

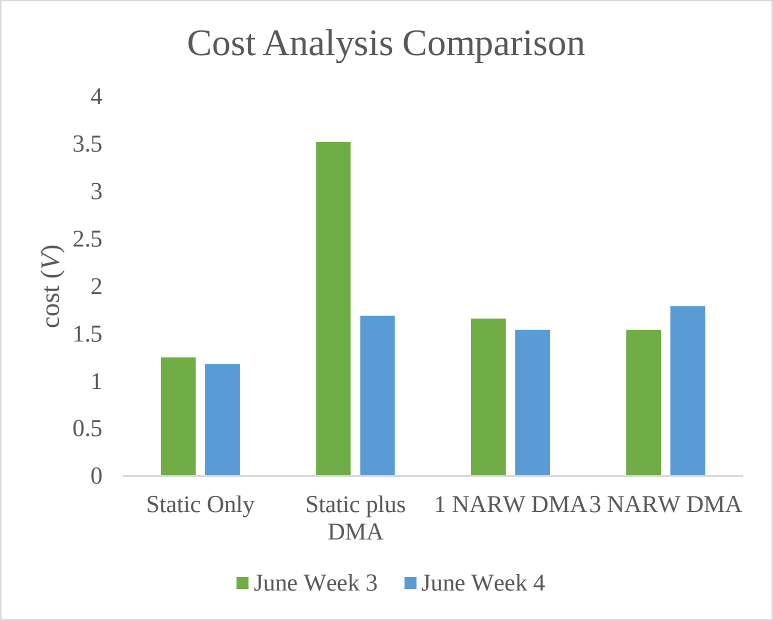


Figure 4.40 Comparison of movement cost approximation for 4 closure scenarios.

4.5. Threat

A base exposure value of the average fishing effort distribution, and for the four closure scenarios was calculated to create a baseline of relative risk to NARWs in the sGSL (Table 4.4); as with the movement cost only week 3 and 4 of June were used for comparison purposes. As can be expected, the regular distribution, with no closures, had the highest overall exposure value: week 3 had a value of 374, while week 4 increases significantly to 2493. The difference between the two weeks is a result of the increase in number of NARWs observed in week 4 versus week 3. Following the no closure exposure level, the static only and the DMA only for 3 NARWs had similar results. The static only closure decreased exposure to 299 in week 3, where was the DMA scenario was able to decrease it to 96. Meanwhile, in week 4, the static closure was able to decrease exposure to a level of 54, compared to the DMA which decreased it to 144. Subsequently, the static plus DMA scenario reduced risk to 96 for both weeks; however, it should be noted that the dynamic closures for this scenario used the real-time 2018 closures, whereas the NARW sightings used in the exposure analysis were from 2017. As a result, the DMA closures for this scenario may not encompass all the 2017 sightings, as such it would be expected if using 2018 data for the exposure level the exposure results would be zero. Meanwhile, the DMA only scenario that closed for a minimum of one NARW did have a calculated exposure value of zero, effectively eliminating the relative risk of fishing gear exposure in the overlapping grid cells.

Table 4.4 Threat estimate for each closure scenario for the month of June, relative to no closure ($T = 1$, thus T = 0 is indicative of a 100% reduction in threat).

Week	Static Only	Static and DMAs	1 NARW DMA	3 NARW DMA
3	0.80	0.26	0.00	0.26
4	0.02	0.04	0.00	0.06

In order to compare the effectiveness of threat reduction between the different closures, and quantify the reduction rate, all closure threat values were compared against the no closure baseline (Table 4.4). As such, the static only closure only reduced exposure by 20% in week 3, compared to 98% in week 4. Meanwhile, the static plus DMA and DMA only for three NARWs were very similar values where week 3 in both scenarios had a reduction value of 74%, and 96% and 94% in week 4, respectfully. Therefore, if using the 2017 data both closures have the same capacity to reduce relative exposure risk. However, as stated above, the one NARW DMA only scenario produced the best results with a 100% decrease in relative exposure during both weeks.

4.6. Cost-Benefit Analysis

A cost-benefit analysis compared the results of the movement cost and the exposure reduction in order to determine to best scenario for the fishery and NARW protection (Table 4.5). Since the cost of the static plus DMA scenario are significantly higher than all the other closure types, as well as has a lower exposure reduction compared some of the other closures, it is considered the worst-case scenario for the fishery. Even with the updated 2018 data and a 100% reduction rate, this strategy is significantly costlier to the fishery than the other closure types. When examining the cost-benefit analysis it is also apparent that although the static only closures have the lowest cost to the fishery, it also provides the least protection to NARWs from exposure to fishing gear. As such, this comparison shows that the best closure would be a DMA only plan that closes for every NARW observed; this has a lower cost compared to the three NARW scenario, and provides the best protection to NARWs through a 100% exposure reduction rate.

Table 4.5 Cost-benefit comparison of relative costs to the fishery (*V*) and relative risk reduction to NARW entanglement (shown in brackets; *Tr*) of all closure strategies. A (-) denotes no analysis, due to either no closures, or no NARW sightings, respectfully.

Month	Week	Static Only	Static plus DMA	1 NARW DMA	3 NARW DMA
April	1	1.14 (-)	- (-)	- (-)	- (-)
	2	1.28 (-)	- (-)	- (-)	- (-)
	3	1.23 (-)	- (-)	- (-)	- (-)
	4	0.56 (-)	- (-)	- (-)	- (-)
May	1	0.98 (-)	- (-)	- (-)	- (-)
	2	1.38 (-)	- (-)	- (-)	- (-)
	3	0.88 (-)	0.75	- (-)	- (-)
	4	1.50 (-)	1.44	- (-)	- (-)
June	1	2.21 (-)	1.18	- (-)	- (-)
	2	1.27 (-)	1.53	- (-)	- (-)
	3	1.25 (*0.80*)	3.52 (*0.26*)	1.63 (*0.00*)	1.54 (*0.26*)
	4	1.18 (*0.02*)	1.69 (*0.04*)	1.54(*0.00*)	1.79 (*0.06*)

5. CHAPTER FIVE: DISCUSSION

This study examined four possible spatial closure configurations – static only, static plus DMAs, and two DMA only closures. The model used in this study was developed with the purpose of investigating the concerns of the fishermen and quantifying the impacts spatio-temporal closures have on both the fishery and conservation efficacy; main concerns revolved around the socio-economic impacts to the fishery and the effectiveness of spatio-temporal closures for NARW entanglement prevention (APPCA & ACC, 2018). The static only strategy was used as a least impact scenario, in which closures would take place at the start of the fishing season, removing the need for the constant surveillance and compliance needed for closures in the DMAs. The static plus DMA scenario was a replica of the closures implemented in the 2018 season; this scenario was important to examine to understand the current effects and real-world impacts this management strategy has on the fishery. Meanwhile, the two DMA only scenarios were used to examine the suggestions of the fishermen, who believe a DMA only closure strategy, in which closures occur when a minimum of three NARWs, versus the current DMA strategy of closures for a minimum of one NARW sighted, presents the best closure strategy option (APPCA & ACC, 2018).

5.1. Socio-economic Impacts of Displacement

Despite the varying number of impacted grid cells, the expected costs from displacement are fairly similar across all four strategies; however, the weekly costs of the static closure are more variable and smaller compared to the DMAs. This variability could possibly be attributed to the unchanging nature of a static only strategy, since static spatial closures tend to not account for the dynamic fluctuations of ocean processes, fish stocks and fleet behaviour (Dunn et al., 2016; Hazen et al., 2018). One such variability is the observation that fishing effort fluctuates on a weekly and monthly basis in the sGSL, with some weeks having heavier fishing activity than others; May accounts for the most productive month for snow crab and is most impacted by the static closure, compared to April, which represents the smallest and most variable number of total landings, or compared to June which has similar fishing activity. Moreover, the static closure, while having a generally smaller number of displaced cells when compared to the strategies with DMAs, also encompasses approximately 22% of the total annual landings of the sGSL. While this study does not include individual vessel information, based on the size of the static closure and the total percentage of annual landings, it can be assumed that the area within the static closure is highly important for the fishery and impacted a large number of license holders. Therefore, a large static closure, such as this one, is likely to result in increased conflict and competition for the next best fishing areas which could then potentially lead to increased environmental impacts and overexploitation of the biomass in the regions outside the closure (Dinmore et al., 2003; Dunn et al., 2016). This increased potential for conflict and competition is supported when we examine the number of sets in the destination grid cells following displacement, where the average number of traps in the most heavily fished grid cells is approximately 115-120 when there was no closure, compared to 300 to 725 sets following the static displacement. These results highlight how easy social impacts such as conflict, and how overexploitation of the regions outside the closure could occur when fishers are competing for the next best fishing grounds.

To expand, conflict and competition amongst different fishermen can occur from displacement since there is less space for the different vessels to distribute between, leading to overcrowding and a host of other socio-economic impacts: closures may increase travel distance, and thus steaming time to reach different fishing grounds, and the increased number of individuals fishing within a certain area can lead to overall decreased CPUE (van der Lee et al, 2013; Slijkerman & Tamis, 2015). This can lead to overarching decreased profits and increased operational costs, as approximated in the cost estimate of this study, for items such as fuel and labour; longer days at sea in order to retain the same profit, resulting in less overall time spent fishing, and increased wear and tear of equipment and thus loss of fishing gear; interactions between gear, increasing the opportunity for loss of gear; decreased catch quality due to longer trip times; safety concerns and personal conflicts due to the longer trip times; and increased careless fishing practices used to cut corners and minimize costs and shorten trip times; developing new relationships at different ports and processing plants. Additionally, the amount of the TAC that each license holder has may exasperate these impacts, as it may no longer be profitable to fish if their quota is too low to offset the costs of movement in the fishery. As such, researchers have suggested that these impacts could potentially result in a fisher permanently exiting the fishery, however, the results of this study indicate minimal fishing loss, or exiting of the fishery ((Dinmore et al., 2003; Dunn et al., 2016). Ultimately, understanding the effects of spatio-temporal closures on fishing effort, and the socio-economic impacts to the fishery is pertinent to designing an effective fisheries management regime; however, as the method presented in this study is a relative approximation, more research would be needed to determine the full extent of these socioeconomic impacts to the sGSL snow crab fishery (O’Keefe et al., 2014).

On the other hand, when compared to static closures, dynamically managed closures have been found to be more effective at minimizing these negative socio-economic impacts (Hobday et al., 2014; Simmons et al., 2015; Dunn et al., 2011, 2016; Hazen et al., 2018). The results of the study show this when examining the expected costs (which includes both social and economic impacts) of the DMAs which are much less variable than the static only scenario. Even more so, the DMA only strategies are even less variable by week than the static plus DMA scenario; this is likely a result of the static plus DMA scenario first being impacted by the initial costs of the static closure, followed by the costs associated with the dynamic closures. While this study does not address the cumulative costs (i.e. the overall costs of the whole fishing season for each management strategy), available literature states that the less time an area is closed, such as with DMAs, the smaller the cost it will have on the fishery (Dunn et al., 2016). The DMAs could also potentially decrease other impacts to the fishery: the DMAs follow the already existing soft-shell crab protocol, a well-known measure utilized in the fishery, thus fishers are already accustomed to adjusting to these types of closures. The fishers understand the protocols of closing specific grids at certain times and adjust to the annual displacement caused by them, therefore a DMA only strategy for NARW protection would not be much different than the current soft-shell crab protocol. The main difference being the potentially shortened temporal scale (for soft-shell the grid is closed for the remainder of the fishing season, whereas they have the potential to reopen in the NARW protocol), and the number of potential closed grid cells. In terms of the temporal scale, researchers have shown that fishing effort will increase in the area after the reopening of the closure, rather than before it is closed (Slijkerman & Tamis, 2015). This is interesting to note as many of the fishermen in the sGSL snow crab fishery are suggesting a later closing date for the static closure, which may still lead to less effort in the static area before it is implemented solely based on the anticipatory closing of the area; therefore, analysis of the difference in cost caused by different closure start dates is suggested to examine these claims. Moreover, the results of this study show that less grids, and thus fishing, were displaced in the DMA only strategies, compared to those with static closures. This suggests that the DMAs would likely be better suited to manage both the spatial and temporal aspects of a potential fishery closure, due to being more flexible and based on real-time NARW sightings, to have the least impacts to the fishery.

Understanding fishermen behaviour is an integral aspect of developing fisheries management solutions, especially when attempting to mitigate the effects of fishing on the marine environment, such as with the case of the sGSL snow crab fishery (Wilen et al., 2002). Harvesters make decisions regarding where and how they fish based on different time scales (hourly, daily, and long-term entry and exit decisions), which are further influenced by various elements; considerations include current and future regulations, available technologies, weather, operating costs, and the abundance and prices of the targeted species (Wilen et al., 2002; Bastardie et al., 2010). Subsequently, when implementing temporary spatial closures, such as with the static area and DMAs in the sGSL, the response of the fishers becomes that much more complicated and important to assess to determine the effectiveness of the closures (Powers & Abeare, 2009). As such, this study used an approximation to determine the preliminary socio-economic impacts caused by spatio-temporal fishery closures; therefore, more work is needed to fully understand the socio-economic impacts discussed above to the sGSL snow crab fishery caused by these closures.

5.2. NARW Protection and Ecological Impacts of Displacement

Similar to the displacement costs to the fishery, the level of threat reduction in all four closure strategies are also comparable. For the purpose of this study, threat referred to the co-occurrence of NARWs and fishing gear in any given grid cell; a threat level of zero meaning there were either no whales or no gear in the grid cell, thus the likelihood of them coming in to contact was null. Similar to the cost analysis, the static closure had the most variable results where the first week with NARW sightings had a 20% reduction in risk, compared to the following week where it increased to 98%. This should be of no surprise, given the previously discussed shortfalls of static closures versus dynamic closures, as well as the fact that the static closure was designed to encompass 90% of the 2017 NARW sightings, which increased significantly between the two weeks of available NARW sightings data. Additionally, current research states that dynamically managed closures have been found to be more effective at reducing by-catch and protecting endangered species (Morzaria-Luna et al., 2012; Hobday et al., 2014; Simmons et al., 2015; Dunn et al., 2011, 2016; Hazen et al., 2018). Therefore, the large threat reduction of the DMAs and the small variability between the weeks further supports current research that recommends dynamic management practices as the most effective method for decreasing bycatch and developing sustainable commercial fisheries (Mozaria-Luna et al., 2012; Dunn et al., 2016; Hazen et al., 2018).

It is also important to note that while the DMAs had less displaced cells than the static closure, across all strategies a total of nine grid cells received the most displaced fishing sets; of these, grids GZ42 and GX39 (Figure 2.3) were the two most commonly chosen location. This is interesting because GZ42 (which received a total of 62 displaced grids and upwards to a thousand sets, when summed across the four strategies) was also the location of a recorded NARW sighting (one whale). This grid cell was only a destination grid for the static closure displacement (in both static closure containing scenarios), further suggesting that dynamically managed closures tend to be more effective for entanglement prevention. In fact, Hazen et al. (2018) found that dynamic spatio-temporal closures could be two to 10 times smaller than a static closure while still providing protection to the targeted protected species. This is seen in the results, as the DMA only scenarios showed to have less displaced grids compared to the static and static plus DMA scenario, while having a higher threat reduction efficacy. Dunn et al. (2016) also suggest that the efficacy of fisheries management improves with dynamic management by increasing the resolution, thus having a more targeted closure with less adverse impacts, which again is supported by the smaller number of impacted cells in the DMA only scenarios, and the consistent costs of the DMAs versus the variable costs and large number of displaced cells in the static closure.

All displaced effort moved to the closest available grid cell to their original location, thus all destination grids resulted in being located around the boundary of the closures (unless a direct boundary grid was unavailable). This suggests two things: these grid cells were the most productive in terms of CPUE, and the concentration of effort around the boundary of the closures creates a "fishing-the-line" effect (Slijkerman & Tamis, 2015; van der Lee et al., 2013; Mason et al.,2012; Murawski et al., 2005). The displaced effort was found to concentrate in a small number of available grid cells, rather than disperse evenly around the entire edge of the closure. As stated in section 5.1, there was a significant increase in the maximum number of sets in the static only displacement results, which is also seen in the static plus DMA scenario (300 to 927 sets). Meanwhile, the number of sets in the destination grids in the DMA only scenarios (160 to 273 sets), combined with the larger number of total destination grids shows that this displacement followed a more dispersed distribution, lowering the potential for a high co-occurrence, as well as minimizing potential conflict in the subset of destination grids. Moreover, displacement did not create a full fence around the closure as some predicted. Due to the characteristics of the snow crab fishery, this effect is not likely due to a spillover effect, as seen in spatial closures aimed at protecting fish stocks, but rather due to the stability and consistency of the fishery resulting in predictable CPUEs per grid cell. Economic factors such as fuel prices can also influence the displacement of fishing effort, as such it can influence the distribution caused by a closure, with fisher's wanting to move to the location with the highest profit and lowest cost ratio; therefore, the distance to port is likely a main contributor to displacement distribution (Slijkerman & Tamis, 2015). However, this study did not have the location of the home ports, therefore it is assumed that since the destination grids are found to be the closest to their original locations within the closed areas, moving to these boundary grids would have the lowest economic costs associated with increased travel. Combined, the minimal travel distance with the highest CPUE would result in the lowest net loss of profit for the impacted fishers.

When implementing spatial closures for environmental protection, it is important to note that there can also be adverse ecological impacts. Environmental impacts caused by displaced fishing effort are primarily categorized in two groups: effects on habitats and/or species, and effects on commercial fish stocks (Slijkerman & Tamis, 2015). Effects on habitats and species are resultant on the amount of fishing effort before and after displacement; the amount of effort displaced, and the type of gear; the density of protected species within the closure area; and additional management measures. Since spatio-temporal closures are often used as a means to achieved EBM, several studies examined the impacts of fishing displacement on the benthic environment and found that if the displaced fishing moved to an area that was already heavily fished, the environmental impacts were small; however, if fishing was displaced to previously lightly fished areas then benthic impact and mortality of invertebrates was high, leading to immediate concerns on biomass, production, diversity and trophic structure (Greenstreet et al., 2009; Dinmore et al., 2003; Hiddink et al., 2006). In the case of the sGSL, snow crab is a bottom-dwelling species, thus it is important to quantify the change in exploitation rate in the open areas to prevent a crash in the snow crab stock. While this study does not examine exploitation rates, the model could be used in future studies to help quantify those changes to help support a precautionary approach to not only address issues with NARW conservation, but to assist in the general management of snow crab biomass and exploitation rates. Moreover, this highlights the importance of achieving equilibrium following spatial closures in order to evenly disperse fishing effort to minimize the negative impacts to the benthic community.

Meanwhile, in terms of bycatch reduction, effectiveness is dependent on the size and timing of the closure (Slijkerman & Tamis, 2015). O'Keefe et al. (2014) examined the effectiveness of closures in several different fisheries, and found that spatio-temporal closures in the Gulf of Maine failed to reduce bycatch of Harbour porpoises in the sink gillnet fishery, since they only considered the areas that were historically fished without considering where the displaced fishing would occur. This is a primary concern when dealing with migratory species, such as NARWs, where a bigger protected area may be necessary, however this may have disproportionately large effects to the socio-economic aspects of the fishery (O'Keefe et al., 2014). In terms of large cetaceans such as NARWs, any fishing lines rising vertically in the water column, such as the pot traps in the snow crab fishery, pose a significant risk of entanglement, indicating the importance of density, distribution, and gear type of displaced fishing effort has on the effectiveness of reducing ecological impacts with a spatio-temporal closure (Brown et al., 2015). Thus, as previously stated, the more targeted resolution of a dynamically manage closure could mitigate both the adverse socio-economic and environmental impacts while providing a large enough protected area for NARWs (Dunn et al., 2016; Hazen et al., 2018).

5.3. Model Assumptions

This model uses a simplistic approach to determine the distribution of effort by selecting the closest grid cell with the highest suitability (CPUE per kilometer traveled). Since fishers are essentially making personal cost-benefit analyses to make these decisions, and due to the complicated nature of predicting individual behaviour, this study assumes that the displaced effort from the closures would move based on the different proportions of catch rates. This is a realistic hypothesis, as a fisher would likely move to an area where they would catch a similar or better amount (thus a higher CPUE) than where they would have before the closure in order to maximize their benefits (Gillis et al., 1993; Powers & Abeare, 2009). However, the model assumes that fishermen are omniscient and know the CPUE of the different fishing areas, and it does not take into account the change of CPUE with the added effort from the displaced fishing (Powers & Abeare, 2009). As such, this model follows a displacement, rather than a redistribution model in which effort keeps moving until a new equilibrium is found (Powers & Abeare, 2009). This could be improved through increased collaboration and discussions with fishermen for future studies to determine how the fleet makes operational decisions; for example, does distance from home port or from the original fishing location dictate displacement response, or does maximizing profit play a more defining role in decision making. Moreover, the cost approximation could be improved by calculating the change in CPUE caused by the increased number of sets in the grid cells following displacement and using these amounts for the cost calculation, which would a provide a more realistic representation of the changes in fishing effort following displacement, and possible impact displacement results.

Moreover, this model also assumes a modified IFD (since we do not assume a new equilibrium is reached), whereas a complete IFD model would take the competitive nature of the fishery into account, since once a grid cell reached equilibrium (maximum set density), they would move to the next grid until that one also reached equilibrium, thus each grid cell has a maximum capacity (Powers & Abeare, 2009; van der Lee et al., 2013). For example, for grid cell GZ42, 68 grid cells from all scenarios, all with different numbers of sets, moved to this grid cells resulting in thousands of sets moving to this location. This is unrealistic as the physical conflict in the space would be too high and the CPUE would decrease too low to make this a viable fishing area for that many sets. Therefore, future analysis should examine the results when a maximum density of sets per grid cells is implemented, and changes in CPUE are calculated. This “maximum” should be determined either through discussions with the fishery, or by examining historical data to determine the maximum number of sets found in a given grid cell based on data with no closures. Nevertheless, the modified IFD displacement model used in this study identifies the areas of main concern, and where the most conflict would likely happen due to the displacement from the current closure configuration, and the possible alternative strategies.

In terms of economically driven behaviour, this model uses CPUE as an approximation for profit and as a criterion for predicting drivers of fleet behaviour and displacement; however, other studies have used value per unit effort (VPUE) instead which provides a dollar amount per unit of effort based on the average prices of the catch (van der Lee et al., 2013). Van der Lee et al. (2013) state that VPUE is more representative of fishermen behaviour, as it "assumes that fishers are more interested in maximizing their total catch value than they are total catch mass and that their fishing activities will be influenced by varying species-specific prices" (p. 980). It is also stated that VPUE and CPUE are often highly correlated, however VPUE provides a more accurate representation of the spatio-temporal variation of effort due to prioritizing the monetary value, rather than the landings (van der Lee et al., 2013). Since fishing behaviour is largely influenced by economics, it is important to include value when examining how a fisher makes decisions based on the costs and benefits of fishing in a given area (Bastardie et al., 2014). However, economic information was not available, thus CPUE was used; therefore, in future analysis, efforts should be made to collect and include available economic information such as the sale price for crab and the average cost of operation, such as labour and fuel costs, in order to determine the average cost of travel per extra km travelled. This would allow for a more accurate representation of the economic costs associated with displacement. Further, it could be beneficial to divide the social and economic costs into two different analysis in order to calculate the most accurate results.

Threat level calculations also used a simplistic method of examining the risk of entanglement, but suits the purpose of this study by providing a quantitative approximation of the probability of a whale coming into contact with gear. While it accounts for the likelihood of co-occurrence, it does not account for the probability of entanglement. As such, future studies should utilize an entanglement probability calculation for a more accurate representation of risk. However, this may be difficult as there is limited data for the sGSL region for NARWs, thus accurate probabilities may be difficult to determine until more sightings have been recorded in order to determine a relative distribution in the sGSL. Additionally, this method does not account for the migratory path of the whales, thus could not account for gear interactions caused by increased gear density in the destination grids, or by a "fishing-the-line" fence, unless a NARW was seen in one of the grids not closed (such as with the 3 NARW DMA closures). Again, this would be difficult to improve on until NARW distribution data for the sGSL is increased, but could potentially be supplemented with other data such as prey distribution, as it is expected the higher density of whales would be found in the regions with the highest density of prey. Moreover, the threat calculations in this study uses a single point of observation, and not the general movement of the NARWs; this could be improved by including a buffer around the sightings (such as the buffer protocol for a DMA closure) to be included as part of the threat calculation, or through increased sightings observations, which would also assist in some of the limitations mentioned above. Finally, this study used 2017 NARW sightings data, as the 2018 data was not available at the time of analysis, however the results of this study would improve vastly from the more comprehensive 2018 sightings data. NARWs were first sighted in mid-May in 2018 versus mid-June in 2017, thus there would be more weeks to compare with the 2018 data. Additionally, the static plus DMA strategy in this study used the 2018 closures, but the 2017 NARW sightings, thus the threat results for this strategy will differ from the actual results (would likely have a 100% threat reduction instead). Consequently, having the most recent and comprehensive data available would provide the most accurate results.

5.4. Preliminary 2018 Season Reports

The NARW consortium recently released preliminary reports of the 2018 season indicating current population estimates, and deaths and injuries from the 2018 summer months (Greenhalgh, 2018). The current population estimates indicated that there is likely only 411 NARWs remaining, and entanglement events remains the leading cause of death in the population. While there were no reported deaths in Canadian waters, three NARWs were found dead in the US and all three were attributed to entanglement, one of which was identified as the result of entanglement in Canadian snow crab gear; however, it should be noted that it is unknown if this was old gear (i.e. lost or abandoned gear) or from the current fishing season. Moreover, there were an additional three reported active entanglements in Canadian territory, indicating that while the new management measures helped to reduce the number of fishery interactions, they are currently not sufficient at reducing all serious entanglement events. While the results of this study suggest a decrease in exposure after the closures, it does not account for the migratory routes of the whales and is only indicative of a single point of observation, which could explain why there were observed entanglements in the 2018 season. The closures are aimed at reducing the risk of entanglement where there are large aggregates of whales, and this study highlights that spatial closures are an effective tool to do so. However, the population estimates indicated the need to further address the transitory pathways of NARWs with increase effort controls and gear modifications to prevent serious entanglement and injuries, which can only be achieved through increased monitoring of the area.

In terms of the closure impacts to the fishery, all fleets were able to catch their quota within the shortened season, with the exception of the traditional midshore and First Nations fleets from QC (DFO, 2018h; 2018k). While there were longer days, and thus some expected economic costs, there was minimal impact in terms of being able to catch the full quota despite closures in the main fishing areas. However, fishermen indicated to DFO that there were global economic impacts caused by the closures (DFO, 2018j). It is likely that these economic impacts were in part due to the suspension of the fishery's MSC certification, which occurred in March 2018 following an audit of the 2017 season (Norsworthy, 2018). The loss of their MSC certification severely limits the market for sGSL snow crab, leading to widespread economic implications. Consequently, it is in the best interest of the fishery to improve their collaboration and NARW protection in order to mitigate these adverse economic effects however, more analysis is needed to fully determine the causes of these impacts.

Moreover, there were excellent response rates to compliance and efforts to remove gear from the closures as soon as possible, as well as increased VMS reporting and gear modifications (DFO, 2018i). However, there was an increase in violations compared to the 2017 season, with the majority of violations dealing with registration, reporting, and other legislation conflicts (DFO, 2018i). There were also some violations in terms of gear: several traps (77) were seized from the DMA closures, as well as from infractions due to floating rope and excess rope violations (DFO, 2018i). As such, another negative was the lack of reporting from the fishermen; a total of 497 traps (1.2% of all allowable traps) were reported as lost, however, the seized traps were not reported as lost gear, which was one of the new management measures put in to place, thus indicating the need for increased communication within the fishery, especially due to the reports of newly entangled

NARWs and one mortality attributed to the fishery (DFO 2018k). Additionally, there was a lack of reporting of marine mammals, and in particular NARW, sightings from the fishery: only 34 reports were submitted for a total of 107 marine mammal sightings, in which only 1 was a NARW (DFO, 2018k). Increased surveillance and NARW distribution information will help to minimize the impacts to the fishery, thus it is in the best interest of the fishermen to assist in these reporting initiatives.

6. CHAPTER SIX: RECOMMENDATIONS AND CONCLUSIONS

Traditional fisheries management follows a single-species approach that does not consider the adverse effects of fishing on the entire ecosystem, particularly on other marine life (Pikitch, 2012). Excessive bycatch rates and impacts to endangered species from commercial fishing practices has been a growing ecological concern, leading to a strong push over the past couple decades for EBM to help address the conflicting ecological, economic and social objectives (Brown et al., 2015; Dunn et al., 2016). Several different management measures and regulations can be used to work towards EBM and address bycatch concerns including gear modifications and bans, effort reductions, quota systems, and spatio-temporal closures (O'Keefe et al., 2014). In the sGSL snow crab fishery, many of these regulations were being utilized in the fishery for many years prior to the 2018 fishing season, including gear specifications, quota and ITQ systems, and short fishing seasons. Following the 2017 NARW mortality event, the fishery implemented spatio-temporal closures in the form of the static and DMA closures. The implementation of these closures led to the displacement of fishing effort, and potentially unintended ecological and socio-economic consequences (O'Keefe et al., 2014; Slijkerman & Tamis, 2015). In order to mitigate these potential impacts, continue to improve NARW conservation efforts, and support an adaptive approach to EBM, this study developed a model to assist in evaluating management measures and making decisions. However, it should be noted that due to the preliminary nature of this study and the limitations presented in section 5.3, the current evaluation makes a final conclusion difficult to assert, thus more research is still necessary. Nonetheless, the results of this study, combined with the available literature, have allowed for several preliminary recommendations to be made, and provide a synthesis of the types of evaluations this model can provide.

6.1. Fishing Closure Strategy

Current fisheries practices are unsustainable and the leading cause of mortality of NARWs, requiring improved approaches in order to mitigate the anthropogenic impacts to their population (Greenhalgh, 2018). In an attempt to mitigate their impact on the NARW population, DFO implemented several new management measures for the sGSL snow crab fishery. However, this was not without push back from the fishermen, with several concerns being raised following the announcement of the new management measures. The majority of concerns were focused on the implementation of fishing exclusion zones, specifically, the timing, size and location of the static closure, and the protocols surrounding the DMAs (DFO, 2018j). Currently, a combined static closure with DMAs is being used to provide a large gear free area for the increasing number of NARWs found in the sGSL. However, results from this study suggest that this is the costliest closure strategy for the fishery, which may lead to increased socio-economic impacts and conflict between industry and government.

Consequently, this study examined alternative closure arrangements and regulations, in which results suggest that the most effective closure type for protecting NARWs, while minimizing the impacts to the fishery, is a DMA only closure system. As mentioned in chapter 5, DMAs provide a higher resolution for more targeted closures that improves endangered species protection while minimizing the amount of closures that may occur in the fishery. Two different protocols for triggering closures in the DMAs were further examined: triggering a closure when at least one NARW has been sighted; and, triggering closures when a minimum of three NARWs have been sighted (DFO, 2018k). Results from this study indicated that the costs to the fishery are similar in both scenarios, yet differ slightly in threat reduction; thus, it is recommended that the DMAs continue to follow the current protocol of closing areas based on at least one NARW sighted, as results from this study show that it provides a larger threat reduction than the three NARW sightings protocol. Ultimately, the results of this study suggest that this strategy is best equipped to adapt to the unpredictive nature of the changing distribution of NARWs to provide the highest level of protection, while minimizing closures and costs to the fishery. However, several limitations have been discussed in section 5.3, therefore, while it is suggested that a DMA only strategy would provide the best outcome, more research is needed to make a full recommendation.

The fishery has also suggested amending the size and duration of the DMAs; however, the recent NARW Consortium report card has indicated that, even with the current measures, NARWs are still being reported entangled in snow crab fishing gear (Greenhalgh, 2018). While this study does not examine the impacts of the timing and size of the closures, it is recommended that the current protocols be maintained in order to continue to provide large gear free areas for NARWs, and to account for their movement patterns in the sGSL, until more research of these protocol is conducted. Moreover, the DMAs also bring concerns over the amount of notice the harvesters receive before needing to remove gear. While this is out of the scope of this project, it is recommended that the minimal amount of time needed is given in order to reduce the threat of entanglement as soon as possible from the time of spotting a NARW, and that further collaboration between industry and government is conducted to determine what this timeframe should be.

6.2. Fishermen Collaboration

The lack of reporting of both lost gear and marine mammal sightings in the 2018 fishing season, despite the new regulations requiring fishermen to do so, is a significant issue that needs to be addressed. The fishery has indicated they want increased NARW monitoring and real-time information regarding NARW sightings. Additionally, a DMA only closure strategy, as recommended in section 6.1, requires increased surveillance within the CFAs; the experience and time spent on the water by the fishermen make them a useful and reliable source for this information (DFO, 2018j). The lack of cooperation from fishermen to assist in these measures may lead to a compromised fishery, distrust from the public, and inhibit NARW research and recovery (Norsworthy, 2018). Moreover, more accurate sightings information can help led to more targeted and smaller closures, and assist in NARW research efforts, consequently, increased marine mammal sighting reporting would be beneficial to all involved. Therefore, it is recommended that both government and industry increase their collaboration and communication to foster a better working relationship and restore trust; this will help lead to increased support and contribution from the fishery. Additionally, it is recommended to increase outreach and educational efforts in order to improve knowledge and compliance with all regulations. Subsequently, the model developed in this study can be used as an outreach tool to show both industry and government the impacts to both the fishery and NARWs caused by fishery closures in order to better quantify and visualize the effects of the different management efforts; this would also help to foster better relationships and increase cooperation.

6.3. Displacement Model as a Management Tool

The model developed in this study provides a novel, precautionary tool that can be used for fisheries and conservation management; it can be used as a real-time monitoring tool, that can be updated as information becomes available. The model was developed to be adaptable and alterations can be made to include additional rules and assumptions, changes can be made to the buffer zone, and it can be applied to other commercial fisheries and species requiring protection. This model can also be combined with other distribution models to provide more comprehensive results. For example, combining the displacement model with NARW prey distribution models can provide more in-depth predictions on the movement and aggregations of NARWs. The benefit of this would be to be able to predict the potential risk hotspots as a result of displacement, as well as account for the predicted movement of NARWs. Subsequently, this information can be provided to the fishery before the fishing season opens, informing them of the predicted closures, thus allowing for increased communication and preparation for the season, effectively increasing collaboration and trust between government and industry.

As discussed in section 5.3, there are several limitations to the model presented in this study which can be improved by including more collaboration and feedback from both industry and government in order to make more accurate rules and assumptions, in particular by incorporating fleet behaviour into the model. It would be useful to speak to fishermen to know the actual distance they would travel from their original fishing grounds for a more accurate buffer calculation. It would also be beneficial to incorporate more concrete economic values into the model. Travel costs could be approximated based on average wages for labour and fuel costs, however, all vessels vary in their efficiency and days at sea, thus would require a more complex method. Since fishing behaviour is largely influenced by economic drivers it would be beneficial to include a more accurate economic profile in the model. Moreover, information regarding individual vessel behaviour, and port locations would allow for more accurate calculations of both displacement and the relative costs.

Next steps of the model include comparing the results of this study with the 2018 VMS data. This would provide a useful comparison between the actual displacement of fishing effort with the predicted distribution based on this study; alterations to the model could then be made to reflect a realistic and accurate portrayal of fishing behaviour. Moreover, it would be beneficial to reassess the different management strategies using the 2018 whale sightings data. There has been an increase in effort of surveillance and monitoring of NARWs in the sGSL in 2018. Thus, increased sightings data would provide a more accurate analysis of the impacts to NARW protection, due to being a more accurate and complete representation of the current whale distribution. Consequently, this highlights the model's adaptability and effectiveness at being used as a long-term management tool to help reassess different management protocols.

6.4. Conclusion

Whales play an important role in the ecosystem as service providers and engineers, heavily influencing ocean productivity through their role in the food chain, and by recycling and providing nutrients (University of Vermont, 2014; Corkeron et al., 2018). NARWs are one of the most endangered whales on the planet, with an estimated population of 411 individuals remaining (Greenhalgh, 2018). Of this population, entanglement in commercial fishing gear represents 85% of all reported human-induced deaths (NOAA, 2018b). The current level of influence human activity has on the population is unsustainable, requiring immediate action in order to assist in the recovery of this endangered species. 2017 was an unprecedented year for NARW deaths, with 17 reported deaths, 12 of which were in the sGSL. It was found that the sGSL snow crab fishery was responsible for at least 2 of these deaths, as well as an additional 5 live entanglements (Daoust et al., 2017). These factors resulted in the Canadian government implementing new fisheries management measures aimed at reducing entanglement events in the sGSL snow crab fishery. These measures included gear modifications to reduce excess rope in the water and improve traceability of gear ownership and locations, a shortened fishing season to reduce the amount of time the fishing activity and NARWs overlapped, as well as fishing exclusion zones in the way of a static closure and DMAs to provide large gear free areas for the whales (DFO, 2018a). While the need to address the anthropogenic impacts on the NARW population is perilous, it is also important to consider the socio-economic impacts closures have on the fishery. The snow crab fishery is the second most lucrative fishery in Canada and employs thousands of citizens; therefore, it is important that new management protocols make the best attempts to also minimize adverse effects to the fishery (DFO, 2018e).

Determining the cost-benefit tradeoffs of the spatio-temporal closures in the sGSL snow crab fishery is an important topic amongst all stakeholders involved. Consequently, this study is the first to quantify the new 2018 sGSL snow crab management measures in order to examine the trade-offs and develop an adaptive management tool. While this study provides a preliminary examination of the impacts to the fishery and NARW protection, current results indicate that the present management strategy of a static closure plus DMAs does not provide enough flexibility in the fishery to keep costs to the fishery low, despite effectively reducing the exposure of NARWs to fishing gear. As such, this evaluation recommends that the fishery changes to a purely dynamically managed fishery, in which the results, supported by current literature, suggest provides the most complete ecological protection while minimizing the socio-economic impacts to the fishery. While there are limitations to this study, and further assessments are needed, the model used can be adapted to assist in evaluating and helping to conclude these types of management decisions. The model is aimed to provide real-time monitoring of displacement activity as a result of fishery closures, and provide fisheries managers with a precautionary tool to improve current NARW protection measures while minimizing disruption to the fishery. Ultimately, by committing to improve fisheries management measures with considerations to both the ecological and socio-economic impacts, Canada could lead by example of the effectiveness of EBM for sustainable natural resource use.

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8. APPENDICES

8.1. APPENDIX A – Geographical Coordinates of sGSL CFAs

Table A1. Geographical coordinates of CFA 12 (DFO, 2013a; DFO 2014a).

POINT	LATITUDE - NORTH	LONGITUDE - WEST
1.	46° 25′ 40″	61° 07′ 00″
2.	46° 37′ 30″	61° 30′ 15″
3.	47° 30′ 00″	60° 43′ 20″
4.	47° 26′ 45″	61° 00′ 00″
5.	47° 50′ 00″	61° 08′ 25″
6.	47° 58′ 30″	61° 07′ 30″
7.	48° 31′ 00″	63° 08′ 30″
8.	49° 00′ 00″	63° 08′ 30″
9.	49° 40′ 20″	64° 54′ 50″
10.	49° 21′ 25″	65° 35′ 30″
11.	49° 17′ 00″	64° 44′ 00″
12.	48° 53′ 30″	63° 48′ 54″
13.	48° 45′ 18″	64° 09′ 54″

Table A2. Geographical coordinates of CFA 12E (DFO, 2013a; DFO 2014a).

POINT	LATITUDE - NORTH	LONGITUDE - WEST
1.	47° 58′ 30″	61° 07′ 30″
2.	48° 02′ 30″	61° 07′ 00″
3.	49° 00′ 00″	63° 08′ 30″
4.	48° 31′ 00″	63° 08′ 30″

Table A3. Geographical coordinates of CFA 12F (DFO, 2013a; DFO 2014a).

POINT	LATITUDE - NORTH	LONGITUDE - WEST
1.	47° 18′ 30″	60° 18′ 00″
2.	47° 21′ 30″	60° 16′ 00″
3.	47° 44′ 30″	60° 25′ 15″
4.	48° 02′ 30″	61° 07′ 00″
5.	47° 58′ 30″	61° 07′ 30″
6.	47° 50′ 00″	61° 08′ 25″
7.	47° 26′ 45″	61° 00′ 00″
8.	47° 30′ 00″	60° 43′ 20″
9.	47° 32′ 12″	60° 42′ 15″
10.	47° 18′ 30″	60° 18′ 00″
11.	47° 21′ 30″	60° 16′ 00″
12.	47° 44′ 30″	60° 25′ 15″
13.	48° 02′ 30″	61° 07′ 00″
14.	47° 58′ 30″	61° 07′ 30″
15.	47° 50′ 00″	61° 08′ 25″
16.	47° 26′ 45″	61° 00′ 00″
17.	47° 30′ 00″	60° 43′ 20″
18.	47° 32′ 12″	60° 42′ 15″

Table A4. Geographical coordinates of CFA 19 (DFO, 2013a; DFO, 2014a).

POINT	LATITUDE - NORTH	LONGITUDE - WEST
1.	46° 25′ 40″	61° 07′ 00″
2.	46° 37′ 30″	61° 30′ 15″
3.	47° 30′ 00″	60° 43′ 20″
4.	47° 16′ 25″	60° 17′ 40″
5.	47° 02′ 15″	60° 24′ 55″

8.2. APPENDIX B – sGSL Snow Crab TAC Breakdown

Table B1. Distribution of CFA 12 TAC for First Nations licence holders (DFO, 2014a).

Region	Percentage of TAC
New Brunswick	8.70%
Quebec	6.24%
Prince Edward Island	0.88%
Total	15.82%

Table B2. Distribution of CFA 12 TAC for Traditional Fleet licence holders (DFO, 2014a).

Region	Percentage of TAC
Midshore, New Brunswick	39.41%
Midshore, Quebec	21.17%
Midshore, Nova Scotia	1.17%
Inshore, Nova Scotia	4.00%
Inshore, Prince Edward Island	3.44%
Total	69.18%

Table B3. Distribution of CFA 12 TAC for New Access Fleet licence holders (DFO, 2014a).

Region	Type	Percentage of TAC
New Brunswick	MFU	6.16%
New Brunswick	ITQ groundfish specialists	0.71%
New Brunswick	Competitive groundfish specialists	0.26%
Quebec	Fixed gear and scallop fleets Gaspe Peninsula	2.17%
Quebec	Fixed gear and scallop fleet Magdalen Islands	0.95%
Quebec	Mobile gear fleet Gaspe Peninsula	0.11%
Quebec	Mobile gear fleet Magdalen Islands	0.45%
Quebec	Lobster harvesters Gaspe Peninsula (RPPSG)	0.89%
Quebec	Lobster harvesters Magdalen Islands (APPIM)	0.27%
Nova Scotia		0.91%
Prince Edward Island	PEIFA	1.87%
Prince Edward Island	PEI Groundfishermen's Association	0.23%
Total		15%

Table B4. Distribution of CFA 12E TAC (DFO, 2014a)

Region	Percentage of TAC
New Brunswick	75.00%
Quebec	12.50%
Prince Edward Island	12.50%

Table B5. Distribution of CFA 12F TAC (DFO, 2014a)

Region	Percentage of TAC
Quebec	68.75%
Nova Scotia	31.25%

8.3. APPENDIX C – Annual Performance of the sGSL snow crab fishery

Table C1. Annual performance of CFA 12 from 2009-2017. Quota and landings revised in tonnes, fishing effort as number of trap hauls, and closed grids out of a total of 323 (CSAS, 2018).

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Quota	20,900	7,700	8,585	18,143	22,548	19,409	23,021	19,393	39,651
Landings	20,896	7,719	8,618	18,159	22,645	19,633	23,080	19,499	39,825
Kg/trap-haul	48.2	47.2	53.0	68.0	76.4	61.8	67.9	64.0	72.0
Trap Hauls	433,527	161,148	162,604	267,044	269,398	317,689	339,912	304,624	553,125
% Soft-shell catch	5.0	6.5	6.2	3.7	2.8	4.4	4.9	5.3	6.0
# Grids closed	78	74	233	7	5	8	41	5	57

Table C2. Annual performance of CFA 12E from 2009-2017. Quota and landings revised in tonnes, fishing effort as number of trap hauls, and closed grids out of a total of 8 (CSAS, 2018).

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Quota	200	67	75	251	204	170	189	144	199
Landings	67	50	76	185	204	178	192	144	203
Kg/trap-haul	14.4	27.4	31.5	32.9	40.1	47.3	65.8	51.5	60.9
Effort (trap hauls)	4,653	1,825	2,413	5,623	5,097	3,765	2,918	2,796	3,333
% Soft-shell catch rate	7.8	14.7	8.4	3.3	15.9	7.8	9.8	1.1	2.0
# Grids closed	2	0	0	0	0	0	0	0	0

Table C3 Annual performance of CFA 12F from 2009-2017. Quota and landings revised in tonnes, fishing effort as number of trap hauls, and closed grids out of a total of 3 sectors (CSAS, 2018).

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Quota	465	420	314	706	543	906	516	373	680
Landings	309	420	313	706	543	882	510	381	684
Kg/trap-haul	22.0	29.3	32.5	41.8	49.0	38.1	38.2	43.9	72.6
Effort (trap hauls)	14,045	14,335	9,631	16,890	11,086	23,163	13,351	8,667	9,421
% Soft-shell catch rate	11.4	8.6	2.6	9.4	2.4	1.7	3.3	10.4	1.9
# Grids closed	3	2	0	0	0	0	0	0	0

Table C4. Annual performance of CFA 19 from 2009-2017. Quota and landings revised in tonnes, fishing effort as number of trap hauls, and closed grids out of a total of 9 sectors.

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Quota	2,433	1,360	1,703	2,907	2,654	3,745	2,130	1,701	2,945
Landings	2,370	1,360	1,701	2,906	2,657	3,745	2,129	1,701	2,944
Kg/trap-haul	71.4	122.1	133.3	178.1	148.5	147.4	144.8	142.5	142.8
Effort (trap hauls)	33,193	11,138	12,761	16,317	17,890	25,407	14,703	11,937	20,616
% Soft-shell catch rate	11.6	6.4	11.5	4.5	3.0	1.0	5.5	8.2	11.6
# Grids closed	9	4	0	0	0	0	2	4	3

8.4. APPENDIX D – Displaced Grid Cell Indices

Table D1. Static only displacement results for April; grid cell index refers to the "new" location of a displaced grid, where as the number of grids moved refers to the number of displaced grids that moved to the that particular grid cell after the closure.

April week 1		**April week 2**		**April week 3**		**April week 4**	
Grid Cell Index	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*
GZ45	1	GX38	7	GX38	7	GX31	1
HC45	1	GZ42	5	GX40	3	GX37	6
		HC42	2	GZ34	1	GZ33	2
				GZ42	5	GZ42	11
				HA34	1	HB42	2
				HC39	2	HC39	2
				HC42	2		

Table D2. Static only displacement results for May; grid cell index refers to the "new" location of a displaced grid, where as the number of grids moved refers to the number of displaced grids that moved to the that particular grid cell after the closure.

May week 1		**May week 2**		**May week 3**		**May week 4**	
Grid Cell Index	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*
GX33	2	GX38	8	GX38	8	GX38	13
GX37	2	GX39	1	GX40	1	GX39	1
GX39	5	GZ33	1	GZ42	4	GZ42	4
GZ42	9	GZ42	8	HA33	1	HA33	1
HA34	3	HB42	1	HB42	5	HA42	1
HB42	2	HC39	3	HC39	6	HB42	1
HC39	5	HD39	4			HC39	6

Table D3. Static only displacement results for June; grid cell index refers to the “new” location of a displaced grid, where as the number of grids moved refers to the number of displaced grids that moved to the that particular grid cell after the closure.

June week 1		**June week 2**		**June week 3**		**June week 4**	
Grid Cell Index	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*
GX37	1	GX38	12	GX39	8	GX33	3
GX38	1	GX41	2	GY42	1	GZ34	3
GX39	15	GZ34	4	GX42	1	GZ42	12
GY34	1	GZ42	1	HA33	7	HC33	1
GZ42	2	HB42	2	HB42	9	HC40	2
HA33	2	HC38	2			HC42	3
HB42	2	HC42	3				
HC39	4						

Table D4. Static plus dynamic displacement results; grid cell index refers to the “new” location of a displaced grid, where as the number of grids moved refers to the number of displaced grids that moved to the that particular grid cell after the closure.

May week 3		**May week 4**		**June week 1**		**June week 2**		**June week 3**		**June week 4**	
Grid Cell Index	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*
GV40	2	GX37	8	GT40	1	GW32	2	GX31	6	GV43	1
GX37	3	GX44	3	GW34	4	GW42	9	GX39	7	GW42	2
GX41	1			GW44	3	GZ34	1	HA33	1	GX31	5
				GX42	3					GY42	1
				GY42	1					GZ42	3
				GZ42	3						

Table D5. Dynamic only displacement results for both the all whale and three or more whale protocols; grid cell index refers to the “new” location of a displaced grid, where as the number of grids moved refers to the number of displaced grids that moved to the that particular grid cell after the closure.

All whales				**3 or more Whales**			
June week 3		**June week 4**		**June week 3**		**June week 4**	
Grid Cell Index	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*	*Grid Cell Index*	*# Grids moved*
GW42	1	GX33	3	GW42	1	GV43	1
GX39	2	GX41	6	GX39	2	GX41	1
GX48	1	GY44	11	GY39	4	GY37	7
GX49	1	GZ34	2	GY43	1	GY44	1
GY39	4	HB36	2	GZ38	1	GZ42	5
GY43	1	HB42	2	GZ43	1	HA36	4
GY44	2	HC42	7	HA38	4	HC42	3
GY49	3	HF48	1	HB42	3		
GZ38	1	HF52	3	HC42	1		
GZ43	2						
HA38	7						
HA45	1						
HA47	2						
HC44	2						
HE42	1						