

**Vessel Dynamics of the Gulf of St. Lawrence Snow Crab (*Chionoecetes opilio*)
Fishery: Examining Spatial Associations and Fishing Success**

by

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Abstract

Fleet dynamics are an important, but understudied aspect of fisheries management. The fleet dynamics of the Gulf of St. Lawrence snow crab (*Chionoecetes opilio*) fishery were examined using two approaches: 1) examining spatial associations based on homeport location, vessel knowledge of the fishery and their impacts on catch rates, and 2) applying an agent-based model to the fishery to examine impact of having pre-season survey information. There were overall higher levels of clustering of vessels who had extensive knowledge of the fishery (traditionals) and the non-traditionals were fishing in similar areas as traditional vessels. Lower levels of clustering were observed among the non-traditional vessels. There were higher total landings with pre-season survey information. Examining how vessels associate gives insight into fleet dynamics, which may be important in management decisions.

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1 Chapter 1 – General Introduction

2 Fisheries are an important contributor to Canada's economy. In Canada, during
3 the 1980's both the Pacific and Atlantic fisheries were considered to be in crisis (Hilborn
4 1985), with resulting consequences on the economy. Pacific salmon and northern cod
5 were hit the hardest and research suggested the main cause was not a shortage of fish, but
6 rather the understudied human aspect of fisheries. The collapses were not due to a poor
7 understanding of the biology of the fish populations but the mismanagement of fishers,
8 decreasing fish prices, the processing facilities and over expansion of fishing fleets
9 (Troadec et al. 1980, Dragesund et al. 1980, Loch et al. 1995, Salas and Gaertner 2004,
10 Branch et al. 2006, Beecham and Engelhard 2007). Hilborn and Ledbetter (1979),
11 Hilborn (1985), Branch et al. (2006), and Fulton et al. (2010) stated that there is still a
12 lack of research on vessel dynamics and the impact on fish abundance. In the past vessel
13 dynamics has led to fisheries crises worldwide and should be a focus in future fisheries
14 research. The complexity of human behaviour could be having unknown effects on
15 fisheries worldwide (Fulton et al. 2010). Fisheries are considered to be the last remaining
16 example of ancestral hunting where there is a discovery and exploitation phase, with the
17 ability for adaptation, creativity and learning (Allen and McGlade 1986, Salas and
18 Gaertner 2004). What make fisheries so difficult to understand are the four main
19 interacting elements: population dynamics, processing, marketing and fleet dynamics,
20 with fleet dynamics being the least studied among them. Fleet dynamics are influenced
21 by ocean climate, hydrology, biological oceanography, fish ecology, and human
22 behaviour (Hilborn 1985, Allen and McGlade 1986) and this complexity may be a
23 primary factor in decreasing fish stocks worldwide. Proper management begins with

24 understanding fleet dynamics and the human behaviour behind communication (Fulton et
25 al. 2010, van Putten et al. 2011).

26 Crashes in fisheries are not only an issue within Canada, but globally as well.
27 Peru experienced a crash in the anchoveta (*Engraulis ringens*) fishery in 1971 (Troadec
28 et al. 1980). As in most fisheries, the Peruvian anchoveta fishery began with rapid
29 development, stabilized, and then began decreasing, but in this case, the decreasing stage
30 led to a commercial extinction. The anchoveta fishery was important not only for human
31 consumption but was the food source for many marine fishes, and for this reason was
32 well studied. Many suggested the collapse was due to the El Niño, but studies now
33 indicate it was poor management strategies in response to a period of low recruitment and
34 higher vulnerability coupled with the El Niño, and by not reducing harvesting during this
35 time. There were studies suggesting there were biological warnings, but the Peruvians did
36 not respond in time, resulting in a fishery exploited to commercial extinction (Troadec et
37 al. 1980, Hilborn 1985). The Norwegian herring (*Clupea harengus*) fishery also
38 experienced a collapse due to poor understanding of the non-biological aspects of the
39 fishery (Dragesund et al. 1980, Hilborn 1985). Management did not respond quickly
40 enough to decreasing fish stocks by lowering the harvest rates. Catch per unit effort
41 (CPUE) was not proportionate to the Norwegian herring stock sizes, and led management
42 to believe the stock was higher than it actually was. There were also issues at the
43 international level of who exactly should be lowering their harvesting rates and economic
44 issues. It wasn't poor understanding of the biology of the herring fishery but issues at the
45 management level in proper understanding of the complexity of CPUE. At the time of
46 these collapses it was generally believed that crashes in stocks were due to an inadequate

47 understanding of the biology of the system, although now, studies conducted by
48 Dragesund et al. (1980), Troadec et al. (1980), Hilborn (1985), Loch et al. (1995), and
49 Beecham and Engelhard (2007) indicated that both of these crashes, along with most
50 declines in fish stock, are due to external factors of the fishery such as fisher behaviour.
51 The next step for fisheries is to study fleet dynamics to examine possible impacts of
52 communication on catch rates and how vessels share their information.

53 Fisher behaviour can be influenced in many ways; such as the price of targeted
54 species, abundance, and the information they obtain while fishing (Salas and Gaertner
55 2004). Information exchange in a fishery can happen in two ways: public, and personal or
56 private (Valone and Giraldeau 1993). Public information is given to all the foragers (the
57 fleet or fishers) on the abundance and distribution of the resources (fish). Private and
58 personal information is gathered by the individual, based on their experience level and is
59 not widely available to the other foragers without direct communication. Fishers develop
60 strategies and knowledge over time, and in many tight knit communities this may be
61 increased through communication. In many fisheries it is difficult to measure
62 communication directly without monitoring radio conversations, and every conversation
63 while at port such as in the study done by Palmer (1991) in the lobster fishery off the
64 coast of Maine. In a fishery where there are a limited number of fishing vessels this might
65 be more feasible than in the snow crab fishery, where there are 200 or more vessels
66 fishing from 86 homeports across four Canadian provinces. Studies have shown that
67 communication reduces the variability around catch rates (Salas and Gaertner 2004) and
68 the time spent trying to find productive fishing grounds (Pöysä 1992). Communication
69 can vary based on the experience of the vessel and how successful they are (Hilborn

70 1985, Salas and Gaertner 2004, van Putten et al. 2011). Not only is communication
71 difficult to measure, it can change over time, changes amongst the different fishing
72 strategies, and there are even short-term changes in fishers behaviour within a season.

73 Studies addressing vessel dynamics are slowly increasing in number and have
74 examined the range of differences in fisheries communication, from sharing frequently
75 (Gillis and Showell 2002), to being secretive, and sharing nothing at all (Anderson 1973).
76 Levels of information sharing are dependent on the fishery, the vessel's crew experience
77 and strategies, and whether it is a specialist or generalist fishery (Salas and Gaertner
78 2004). A study done by Anderson (1973) showed that trawlers tried to control their
79 information rather than sharing it and some skippers even created code to ensure their
80 information was private. On the other hand, a study done by Gillis and Showell (2002)
81 showed that in the silver hake (*Merluccius bilinearis*) fishery off the coast of Nova
82 Scotia, fleets shared their information frequently amongst themselves. Studies on the
83 Maine lobster fishery (Acheson 1975, Palmer 1991) concluded there was some form of
84 communication occurring amongst vessels, as there are certain areas that are restricted to
85 newer fishers where the experienced fishers will not allow them to fish. Palmer (1991)
86 stated that the lobster fishers off the coast of Maine are known to go to great lengths to
87 protect their knowledge and are the most secretive fishers on the coast. He was able to
88 monitor communication between vessels by listening to radio conversations and talking
89 to crew while at dock in a small fishery, and had adequate representation of
90 communication. A reason for communicating can be to help out their friends or family
91 members to ensure they meet their quotas. Communication amongst the fleet may help
92 decrease the uncertainty around catch variability (Salas and Gaertner 2004) as well as

93 decrease the time spent foraging for productive areas (Pöysä 1992). The main issue with
94 analysing vessel dynamics is that normally it is difficult to measure communication
95 between vessels without monitoring radio communication or communication while at
96 port. Cooperation is fluid and changes over time, and may be dependent on the success of
97 those in the group and is another reason measuring communication is difficult. This thesis
98 will examine spatial associations, which are presumably the result from communication,
99 in the Gulf of St. Lawrence snow crab fishery.

100 *Chionoecetes opilio*

101 Snow crabs are crustaceans with a flat, round body and are measured by their
102 carapace width. They have a complex life cycle where they grow through a molting
103 process in which they shed their old shell and a soft new one forms that will eventually
104 harden with a larger size than the previous (Siddeek et al. 2009). Unlike lobsters, snow
105 crabs do not molt their entire lives. Just after they have molted, the shell is white and
106 extremely soft, and at this point is known as a “white crab”. When the shell hardens and
107 ages, they become a green-brown colour with a yellow ventral side (Fonseca et al. 2008).
108 A snow crab will reach its final molt known as their terminal molt once they have
109 reached sexual maturity. Before their terminal molt they are known as an immature or
110 adolescent crab (Siddeek et al. 2009). Females stop growing once they attain a wide
111 enough abdomen to carry their eggs, which is less than 95 mm (DFO 2016). Since female
112 carapace width (CW) does not exceed 95 mm, management can effectively protect them
113 by only allowing snow crabs with a CW greater than this to be fished (Swain and Wade
114 2003, DFO 2016). Full-grown males can be almost twice the size of female crabs but stop
115 growing once they develop large claws on their first pair of legs which usually occurs

116 once their CW is between 40-150mm (DFO 2016). Males tend to live 5 to 7.7 years after
117 their terminal molt (Sainte-Marie et al. 1995, Fonseca et al. 2008). Female snow crabs
118 carry their eggs under their abdomen for about two years in the Gulf of St. Lawrence
119 (GSL). The eggs hatch in the late spring/early summer. The crab larvae will then spend
120 on average 12-15 weeks in the water column before settling to the bottom of the ocean
121 (DFO 2016).

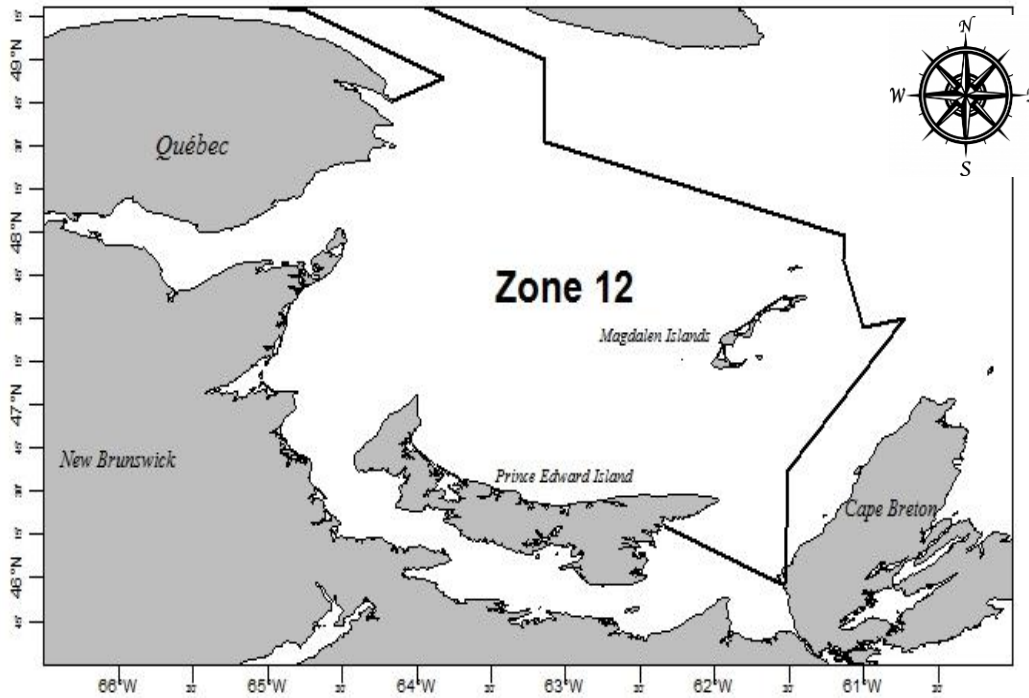
122 Mature snow crab live in muddy or sand-mud bottoms at a temperature range
123 from -0.5 to 4.5 °C at depths of 70-140 m. Females remain together in larger groups
124 while males distribute themselves more randomly (Biron et al. 2008). After tagging
125 experiments in the GSL were conducted, it was observed that there were no patterns in
126 the seasonal movements of male snow crabs. They are slow moving but results show that
127 even though 80-90% of the males were recaptured within 25 km from their release point,
128 some had travelled up to 50 km in less than a year meaning they are not sedentary (Biron
129 et al. 2008). It is not well documented where the juvenile snow crabs live. Since snow
130 crabs are slow moving, the survey data collected at the end of each season by Fisheries
131 and Oceans Canada (DFO) can provide a fairly accurate representation of what next
132 season's snow crab distribution will be.

133 **The Fishery**

134 The GSL snow crab (*Chionoecetes opilio*) fishery began in 1965 when the
135 Government of Canada explored the Gulf for the potential of a fishery (Hare and Dunn
136 1993, Loch et al. 1995, Comeau et al. 1998). Presently the Canadian snow crab fishery is
137 located on the east coast of Newfoundland and Labrador, in the estuary, GSL, and around
138 Cape Breton Island. The GSL fishery is split into different management areas and the

139 focus will be on zone 12 (main midshore fishery) (Figure 1.1). Area 12 is the largest in
140 terms of area, landings, and number of vessels fishing (DFO 2016) and will be the focus
141 of this thesis. After the collapse of the Atlantic cod (*Gadus morhua*) fishery the snow
142 crab fishery flourished (Boudreau et al. 2011). By 1988 the fishery was producing \$150
143 million per year and then in 1989, appeared on the brink of a collapse (Hare and Dunn
144 1993). After this significant decrease in snow crab abundance, management and industry
145 have cooperated in maintaining a long-term sustainable fishery (Caddy et al. 2005). The
146 fishery is now considered to be well-managed (Loch et al. 1995) by implementing
147 strategies such as protecting female snow crab by only allowing males to be fished,
148 limiting the fishing season, monitoring the total allowable catch (TAC) which is then
149 divided into individual quotas, limits on traps, the percentages of total catches that are
150 white crabs, and monitoring of fishing grids (Comeau et al. 1998, DFO 2016). These are
151 common strategies in many fisheries (Salas and Gaertner 2004) and are effective, but the
152 snow crab population is still on a slow and steady decline, so further research into other
153 aspects of the fishery is required.

154 Each fall an annual survey takes place after the fishery ends to estimate the
155 number of commercial-sized males and females to determine the recruitment and
156 population biomass for the next season. The annual survey is done using kriging to
157 determine the total allowable catch (TAC) and estimates of the snow crab biomass for the
158 next fishing season (Sideek et al. 2009). Kriging is performed with external drift (a
159 geostatistical technique) (Webster and Oliver 2001) using depth as a secondary variable
160 (Wade et al. 2014). Kriging is done to estimate a random variable at one or more
161 unsampled areas. The drift represents a mean that is not stationary. The information from



163 **Figure 1.1** A map of the Gulf of St. Lawrence snow crab fishery. **Zone 12** is the focus
 164 **for the thesis, as it is the largest in terms of size and number of vessels fishing each**
 165 **season. Vessels originate from four provinces: New Brunswick, Quebec, PEI, and**
 166 **Nova Scotia.**

167

168 this survey is given to every vessel at the beginning of the next season, and for this thesis
169 will be considered as public information.

170 The fishery is made up of three types of vessels; traditional, non-traditional and
171 First Nations vessels. For this thesis, the First Nations vessels were dropped from
172 analysis as only a couple (0-3 per year) were fishing throughout the years studied.
173 Traditional vessels were the original vessels that have been fishing since the 1960's.
174 Traditional vessel licenses can be passed down within a family (DFO 2016, E. Wade,
175 Gulf Fisheries Centre DFO, Moncton, Canada, personal communication, 2016). The
176 traditional vessels are allocated a maximum of 150 traps per licence (Charles et al. 2014,
177 DFO 1995, Gillis et al. 2006). The non-traditional vessels tend to be lobster fishers who
178 come into the snow crab fishery in years when the lobster biomass is low (Gillis et al.
179 2006). Therefore the traditional vessels crews tend to have more knowledge of the fishery
180 in comparison to the non-traditional vessels. The non-traditional vessels are given a
181 maximum of 50 traps, due to their smaller-sized vessels. The fishers use baited wire or
182 steel traps (DFO 2016). Licence allocations are decided at the beginning of the season
183 from the results of the post-season survey the previous year.

184 Fishing vessel behaviour is made up of multiple aspects: economic, sociological
185 and information science (Salas and Gaertner 2004). Inadequate understanding of these
186 aspects by management can cause severe consequences, or the extreme result of a
187 complete loss of the fishery, as in the case of the anchovy fishery (Troadec et al. 1980).
188 The GSL snow crab fishery has been closely monitored each year by DFO since its
189 opening, by monitoring total allowable catch (TAC), effort controls (the number of
190 licenses given out, trap limits, and season length) as well as an imposed limit on the

191 percentage of soft-shelled crabs allowed in a catch (Siddeek et al. 2009). Another way
192 that the fishery is limited is by only allowing snow crabs with a CW larger than 95 mm to
193 be harvested (Comeau et al. 1998, Siddeek et al. 2009, Émond et al. 2015) effectively
194 protecting females who never reach this size.

195 The fishery starts in spring once the ice has melted and ends once the vessels
196 individual quota is met as well as the TAC (Siddeek et al. 2009). Over the years,
197 fluctuations have been observed in the snow crab population, but a large decrease was
198 seen in 1986 (Loch et al. 1995, Caddy et al. 2005). Due to this large decrease,
199 management enforced stricter regulations to protect the fishery (Loch et al. 1995). Since
200 1988, there have been two significant periods of high and low snow crab abundance in
201 the GSL with the lows in the late 80's and in 2000, and the larger peaks from 1992-1994
202 and from 2003-2006. These highs are much lower in comparison to the 1970's after the
203 fishery first opened. The biomass peaks are generally always lower than the previous
204 peaks and the lowest levels higher than the previous. The reasons for these fluctuations
205 are unknown but could be due to high natural and/or fishing mortality as well as
206 environmental factors (Siddeek et al. 2009).

207 The crab fisheries face similar risks as other fisheries in terms of population
208 crashes; they have also been observed in the Japanese snow crab fishery in the mid-
209 1970's, and the Alaskan crab fishery in the mid 1980's (Loch et al. 1995, Hardy et al.
210 2011). Due to these crashes and the need for crab in these locations, the snow crab fishery
211 in the GSL's leading exports are to the United States of America and Japan (E. Wade,
212 Gulf Fisheries Centre DFO, Moncton, Canada, personal communication, 2016). Although
213 the GSL snow crab fishery is well studied, there is a lack of knowledge on fleet dynamics

214 and the impacts on catch rates. A first step toward understanding fleet dynamics is to
215 examine whether vessels are fishing in similar areas. Spatial associations can have one of
216 three outcomes, clustered, dispersed or random distributions. It is impossible to measure
217 communication in this fishery, but it is possible to look at fishing location patterns using
218 available data on: homeport location and vessel type. Understanding spatial distributions
219 in ecological contexts has been stressed by Dixon (1994) to implement better
220 management strategies and understanding of the system's dynamics. The result of social
221 interactions on fishing effort allocation can be examined by exploring possible factors
222 influencing information sharing and how vessels are distributed on the water. Catch rates
223 and abundance may be influenced by fish distribution and how fishing vessels allocate
224 their effort (Hilborn and Walters 1987, Holland and Sutinen 1999). Coupled with proper
225 understanding of the biology of the snow crab, examining vessel dynamics in the future
226 could help explain how vessels are associating in the snow crab fishery and thus have
227 possible implications for the stock, and help inform management in establishing
228 successful harvest strategies. The biology of snow crab is well studied, therefore the next
229 step is to examine the social aspects of the fishery to help prevent a crash in one of
230 Canada's most lucrative fisheries.

231 **Thesis Goals**

232 The goal of this thesis is to examine spatial associations in the GSL snow crab
233 fishery and is divided into two main sections. The first (Chapter 2) examines spatial
234 associations among fishing vessels and patterns in fishing success (catch rate). The
235 second (Chapter 3) develops an agent-based model using historical abundance patterns of
236 the GSL snow crab fishery to probe possible factors effecting effort allocation and fishing

237 success. The results of this model solidify the conceptual model of the fishery and
238 highlight future hypotheses for investigation. After examining the results of spatial
239 associations between the vessels of the snow crab fishery, an agent-based model (ABM)
240 will be applied to the data collected by DFO, making up Chapter 3. Incorporating the
241 fishery's data into an ABM will allow me to explore the effects of varying levels of
242 communication and its impact on spatial associations of the fleet. This gives a base model
243 that can in the future be used to model the impacts of implementing different
244 management strategies to examine the performance of regulation protocols (Watson et al.
245 1993, Lempert 2002).

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376

377 **Chapter 2 – Impacts of Vessel Dynamics of the Gulf of St.**
378 **Lawrence Snow Crab (*Chionoectes opilio*) Fishery on Spatial**
379 **Associations and Catch Rates**

380 **Abstract**

381 The snow crab fishery in the Gulf of St. Lawrence exhibits a quasi-cyclic
382 population trend on a slow and steady decline. The fishery is made up of traditional and
383 non-traditional vessels from four Canadian provinces. My goal was to analyze vessel
384 dynamics and the resulting impacts on spatial association and catch rates. Associations
385 between vessels from similar homeports and vessel types were analyzed using Mantel
386 tests, and Ripley’s K function respectively and trends in catch rates were modeled using
387 additive mixed models. There were higher levels of clustering between traditional vessels
388 and amongst the two types than just the non-traditionals. Traditional vessels also had
389 higher catch rates. Catch rates were higher at the beginning of seasons and decreased as
390 the fishing season progressed. Information is being exchanged preferentially within
391 vessel types in the fishery, resulting in performance differences, and should be considered
392 when interpreting or regulating fishing activity.

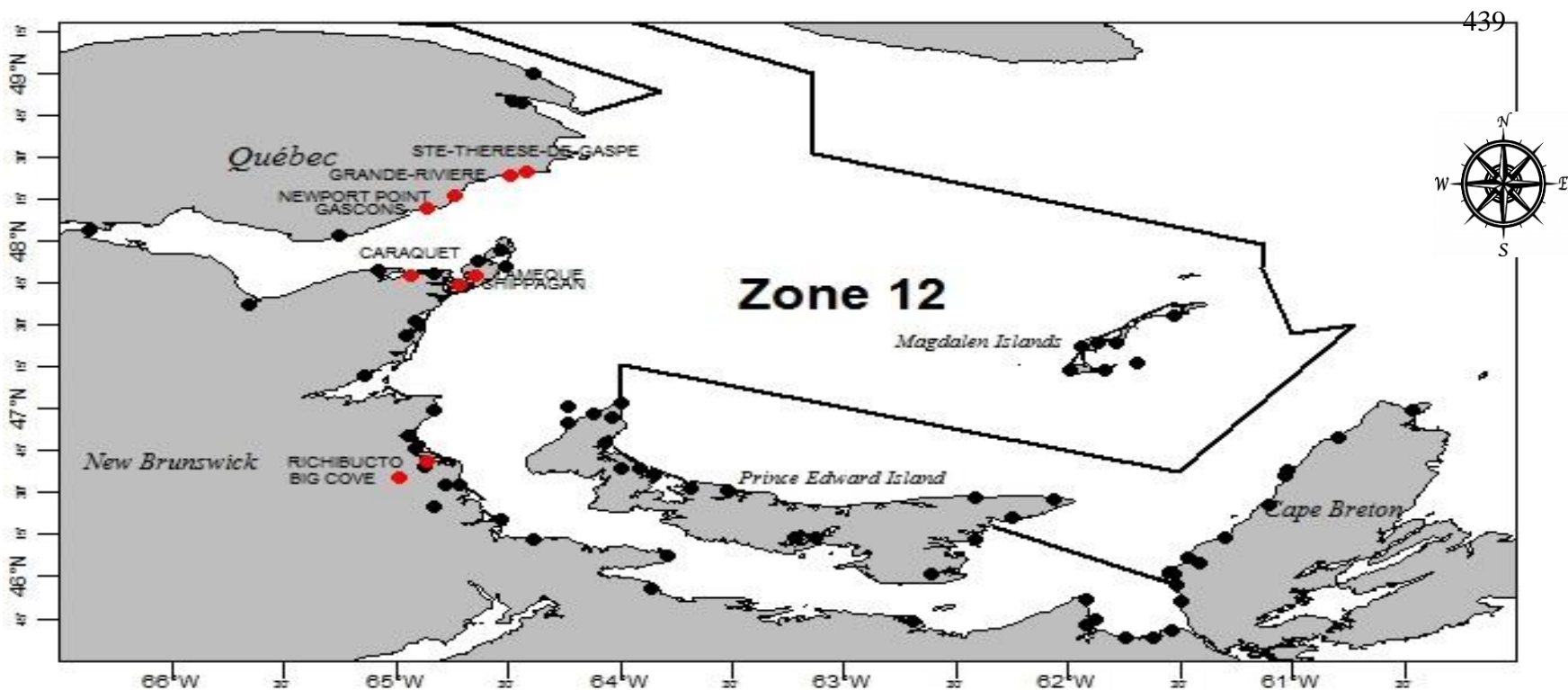
393 **Introduction**

394 In the 1980's, Canada experienced a fisheries crisis in both the Atlantic and
395 Pacific, where salmon, cod, and herring were hit the hardest but many other species saw
396 declines in their populations (Hilborn 1985). This had significant repercussions for
397 Canada's economy. Studies suggest these crises were not caused by the lack of fish, but
398 rather external factors such as increasing fleet numbers, processing facilities, stock prices
399 and possibly the fleet's dynamics (Kirby 1982, Pearse 1982). Hilborn (1985) stated that
400 decreasing fish populations are not only a problem in Canada but are considered a global
401 issue, and are the result of not understanding the fisher's behaviours, which leads to
402 mismanagement of the fishery. There is presently a lack of research on this important
403 aspect of management according to Branch et al. (2006). Fisheries are complex systems
404 made up of the marine ecosystem, ocean climate, hydrology, biological oceanography,
405 fish ecology and the human system, which includes the crew of each vessels knowledge
406 and their behaviour (Allen and McGlade 1986). Hilborn (1985) described fisheries as
407 involving four interacting elements: population dynamics, processing, marketing and
408 fleet dynamics, and while the first three are well studied, fleet dynamics are not. This
409 leads to a gap in knowledge where management struggles to estimate the overall impacts
410 on fish populations by unsuccessfully tying all these four elements together.

411 Hilborn (1985) stated that other countries such as Peru (anchoveta fishery)
412 (Troadec et al. 1980), and Norway (herring fishery) (Dragesund et al. 1980) have also
413 seen major collapses in their fisheries due to external factors and not an inadequate
414 understanding of fish biology (Beecham and Engelhard 2007). At the time of these
415 collapses it was generally believed that crashes in stocks were due to a deficient

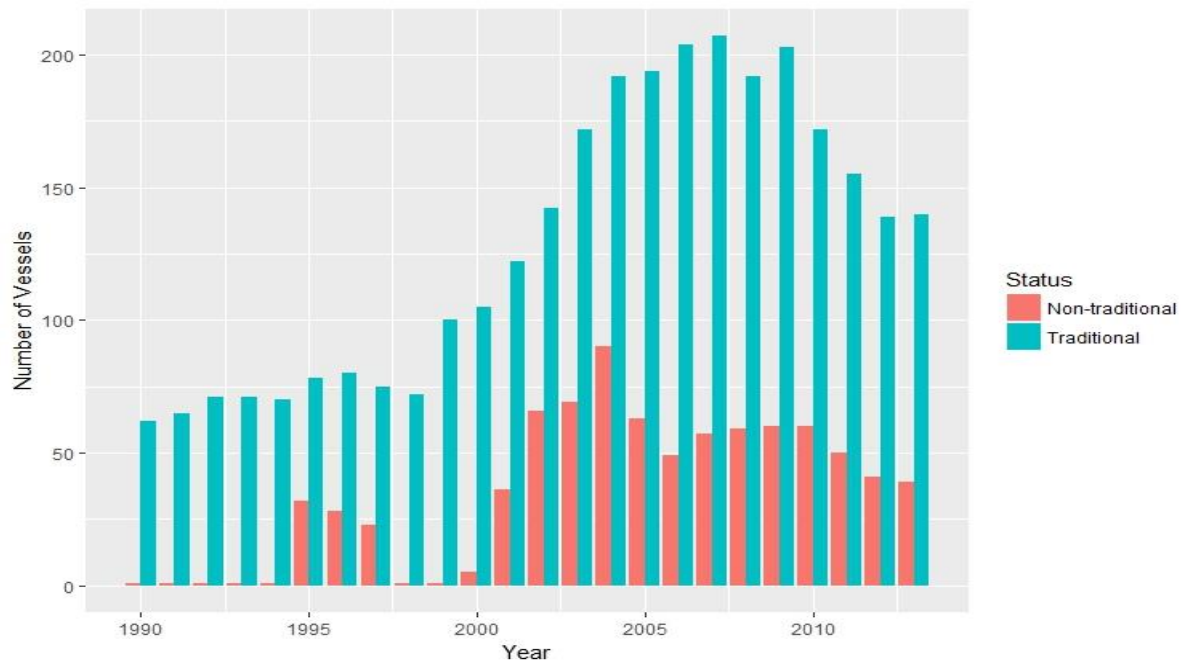
416 understanding of the biology of the system, although now, studies conducted by
417 Dragesund et al. (1980), Troadec et al. (1980), Hilborn (1985), and Loch et al. (1995),
418 indicate these crashes were due to external factors of the fishery such as fisher behaviour.
419 The crab fisheries face similar risks as there were also crashes seen in the Japanese snow
420 crab fishery in the mid-1970's, and the Alaskan crab fisheries in the mid-1980's (Loch et
421 al. 1995). Due to these crashes, the snow crab fishery in the Gulf of St. Lawrence's
422 leading exports are to the United States of America and Japan to meet their demands (E.
423 Wade, Gulf Fisheries Centre DFO, Moncton, Canada, personal communication, 2016).
424 Management's goal is to maintain sustainable fish stocks to ensure quality fish as a food
425 source, create jobs, and provide steady income (Branch et al. 2006).

426 The Gulf of St. Lawrence (GSL) snow crab (*Chionoecetes opilio*) fishery is
427 considered to be a well-managed fishery (Loch et al. 1995, Comeau et al. 1998, Émond et
428 al. 2015) but has a quasi-cyclic population that is on a slow decline (DFO 2016, E. Wade,
429 Gulf Fisheries Centre DFO, Moncton, Canada, personal communication, 2016). The GSL
430 snow crab fishery is one of eastern Canada's most important economic fisheries and the
431 main focus for this study is on zone 12 (Figure 2.1) (Loch et al. 1995, Biron et al. 2008,
432 Charles et al. 2014). The fishery began in the mid 1960's off Québec, and today has two
433 main types of vessels fishing: traditional and non-traditional vessels from Québec, New
434 Brunswick, Nova Scotia, and Prince Edward Island with 86 total homeports (Figure 2.1).
435 Traditional vessels have been in the fishery since at least 1997, while some have been
436 fishing since the 1960's (Pinfold 2006, E. Wade, Gulf Fisheries Centre DFO, Moncton,
437 Canada, personal communication, 2016). The total number of licenses varies around 200
438 (Figure 2.2) and is dependent on pre-season survey data collected by the Department



440 **Figure 2.1** A map of the Gulf of St. Lawrence snow crab fishery. Zone 12 is the focus for the thesis as it is the largest in terms
 441 of size and number of vessels fishing each season. Vessels originate from four provinces: New Brunswick, Quebec, PEI, and
 442 Nova Scotia. The black and red points represent all the homeports, while the red points are the nine homeports from the focus
 443 dataset with their names (Ste-Therese-de-Gaspe, Grande-Riviere, Newport Point, Gascons, Caraquet, Lameque, Shippagan,
 444 Richibucto, and Big Cove).

445



446 **Figure 2.2** A bar graph looking at the number of licenses given to each type of vessel
447 (Traditional in blue and non-traditional in red) per year.

448

449 of Fisheries and Oceans Canada (DFO) on snow crab abundance. Traditional vessel
450 licenses can be passed down within a family (DFO 2016, E. Wade, Gulf Fisheries Centre
451 DFO, Moncton, Canada, personal communication, 2016). Therefore, traditional vessels
452 crews tend to have more knowledge of the fishery in comparison to the non-traditional
453 vessels crew. License trap limits are associated with vessels. Traditional vessels are
454 allocated a maximum of 150 traps per licence (Charles et al. 2014, DFO 1995, Gillis et al.
455 2006). The non-traditional vessels tend to be lobster fishers who come into the snow crab
456 fishery in years when the lobster biomass is low (Gillis et al. 2006). They are given a
457 maximum of 50 traps, due to their smaller-sized vessels (Charles et al. 2014, Gillis et al.
458 2006). Since the large decrease in snow crab numbers seen from 1987-89, fishers have
459 been working closely with DFO to maintain a sustainable fishery (Loch et al. 1995),
460 although numbers are still on a slow but steady decline (DFO 2016).

461 Hilborn (1985), Salas and Gaertner (2004) and Branch et al. (2006) have stressed
462 that the lack of studies in fleet dynamics and studying fishers behaviour have had huge
463 impacts on many fishery collapses. Vessel dynamics are fluid and dependant on the
464 amount of information shared through multiple forms (verbal or visual) of
465 communication, which is difficult to measure in this fishery. The next step to properly
466 manage the fisheries is to instead look at spatial associations, which is presumably the
467 result of information exchange (Palmer 1991, Gillis et al. 2006).

468 Over the past decades, the study of vessel dynamics is slowly becoming more
469 popular in fisheries research. A study done by Anderson (1973) showed that trawlers
470 tried to control their information rather than sharing it and some skippers even created
471 code to ensure their information was private. On the other hand a study done by Gillis

472 and Showell (2002) showed that in the silver hake (*Merluccius bilinearis*) fishery off the
473 coast of Nova Scotia, the fleets shared their information frequently amongst themselves.
474 In a similar fishery to the snow crab, the Maine lobster (*Homarus americanus*) fishery,
475 there are certain areas that are restricted to newer fishers where the experienced fishers
476 will not allow them to fish according to Acheson (1975) and Palmer (1991). Palmer
477 (1991) stated that the lobster fishers off the coast of Maine are known to go to great
478 lengths to protect their knowledge and are the most secretive fishers on the coast. In the
479 GSL snow crab fishery, Gillis et al. (2006) showed that there was evidence of
480 information exchange that impacted fishing effort and could help inform management
481 strategies. Gillis et al. (2006) looked at whether the different vessel types from a similar
482 homeport were fishing in close proximity. The Gillis et al. (2006) study is a finer scale
483 study than this analysis where I look at the broader scale of associations using different
484 methodology with a larger dataset. This will allow us to obtain a broader understanding
485 of the possible communication occurring within the fishery.

486 Further exploration into the larger scale dynamics of the snow crab fleet is needed
487 to determine the impacts the different vessels or homeports have on the snow crab
488 population across years. According to Beecham and Engelhard (2007), fisher's behaviour
489 is made up of three main aspects: economic, sociological and information science. A lack
490 of understanding of these aspects can potentially be problematic for management if the
491 stocks decrease too quickly to maintain a sustainable fishery (Branch et al. 2006,
492 Beecham and Engelhard 2007). Understanding spatial distributions in ecological contexts
493 has been stressed by Dixon (1994) to implement better management strategies and to
494 promote a better understanding of the system's dynamics. Vessels are out for economic

495 profit, but the social aspect of the fishery is what I will examine with this analysis, by
496 looking at possible ways information is being shared and at how vessels are distributed
497 on the water.

498 Information exchange in a fishery can happen in two ways: public, and personal
499 or private (Valone and Giraldeau 1993). Public information is given to all the foragers
500 (fishers) on the abundance and distribution of the resources (snow crab). Private and
501 personal information is gathered by the individual, based on their experience level and is
502 not widely available to the other foragers without direct communication. Both are
503 possible in the GSL snow crab fishery through pre-season surveys (public), in-season
504 communication and personal experience (private and personal).

505 With so many vessels fishing in zone 12, communication between vessels could
506 cause high levels of aggregation at fishing locations, which may lead to overfishing.
507 Branch et al. (2006) and van Putten et al. (2011) suggested that vessels from similar
508 homeports are likely family members or close friends so would be more likely to
509 communicate and indicate the location of a profitable area to each other. This overfishing
510 could then in turn lead to local decreases in snow crab abundance (Branch et al. 2006,
511 van Putten et al. 2011). If high abundance areas (hotspots) are located, and multiple
512 vessels continue to fish it, there is the potential for drastic decreases in the abundance of
513 stock at that location impacting recruitment, survival and abundance for the following
514 years. Therefore, understanding how vessels associate could help management determine
515 if certain locations are being targeted and the impact of clustering of vessels in these
516 areas on catch rates.

517 Another form of association that may be occurring could be between vessels of
518 similar or dissimilar levels of experience within this fishery (traditional vs. non-
519 traditional). Crews of traditional vessels would likely know most, if not all, crews of the
520 other traditional vessels within the fishery and they may be friends or family members, as
521 they have been fishing together since at least the 1990's and therefore may be more likely
522 to communicate between themselves. Hoppitt et al. (2008) stated that when learned
523 information is shared amongst individuals, it is rare that experienced individuals share
524 their information with the less experienced individuals in a population. Although
525 information isn't routinely being directly shared in nonhuman mammal's daily activities,
526 they may still provide information to other individuals that they are not actively sharing
527 (Galef and Giraldeau 2001). Considering that traditional vessels have permanent
528 allocations in the fishery they may be less inclined to help out the non-traditional vessels,
529 which are likely strangers and are less invested in the long-term goals of the fishery. This
530 may result in a lower chance of communication from traditional vessels to the non-
531 traditional vessels but not necessarily the other way around.

532 Local enhancement may be a contributing factor in vessels associating on the
533 water. According to Pöysä (1992) local enhancement can occur at fine and coarse levels.
534 Fine-level enhancement suggests that vessels would have higher catch rates (feeding
535 rates) if they were in a group and would be copying each other's foraging behaviour.
536 Coarse-level would suggest that when grouping is occurring in highly abundant areas,
537 this attracts other foragers to the same area. Whether the leading contributor is fine or
538 coarse level local enhancement or a combination of the two, this would suggest that there
539 may likely be associations between certain vessels on the water (whether they form a

540 “group” based on the level of communication as discussed previously) and this could
541 further attract other vessels to similar areas resulting in many vessels clustering while
542 fishing. It is likely with the snow crab fishery that coarse-level local enhancement may be
543 the contributing factor. In either case the main outcome of local enhancement is increased
544 feeding/foraging efficiency (Pöysä 1992). Studies in nonhuman mammals have shown
545 that clustering of less experienced/juvenile (non-traditional vessels) individuals occurs
546 when individuals observe a mature/experienced (traditional vessels) conspecific at a
547 foraging ground (Galef and Giraldeau 2001).

548 Snow crab abundance is related to catch rates. With increasing catch, abundance
549 will slowly and not always proportionally, decrease, so it is important to see how fishing
550 parameters impact catch rates to more accurately follow abundance trends. Zone 12
551 encompasses 86 homeports situated across the four provinces (Figure 2.1). The number
552 of vessels varies between ports, as well as across years. The total catch across these
553 homeports could vary depending on the amount of vessels fishing during the season and
554 the type of vessels from these ports. Beverton and Holt (1957) and Kimura (1981) stated
555 that catch per unit effort (CPUE) is proportional to abundance. When abundance is high,
556 vessels wouldn’t have to set as many traps to catch snow crabs while in lower abundance
557 years, effort will be higher and catch will be lower. This is not always necessarily the
558 case (Harley et al. 2001, Maunder et al. 2006). Maunder et al. (2006) discussed the issues
559 that arise with assessing fish stocks using CPUE. CPUE is rarely proportional to
560 abundance as there are so many factors affecting CPUE. Standardizing CPUE data is
561 fairly common in fisheries research to estimate abundance, but leaves little to be known
562 about how to manage a fishery or the effect of fishing on population and thus, other

563 models can be incorporated to improve these abundance assessments. Catch may be
564 dependent on yearly snow crab abundance. As previously discussed, vessel type will
565 likely have an impact on catch rate. Since crews of traditional vessels have longer and
566 more extensive knowledge of the fishery, they will likely have higher catch rates than the
567 non-traditional vessels. Catch rates will vary across different days of the year with higher
568 catches occurring at the beginning of the season. Analysing vessel dynamics and
569 examining how vessels may be clumping may assist management in setting strategies for
570 the fishery by improving their ability to follow changes in abundance and predict the
571 effects of changing fleet activity and composition.

572 **Materials and Methods**

573 **The Fishery**

574 The southern GSL snow crab fishery is comprised of different management zones
575 and the focus of this thesis is on zone 12 (Figure 2.1) from 1990-2013. The data
576 employed in my analysis were collected by DFO, using landing slips and their yearly pre-
577 season surveys. The landing slips provided information on the vessels latitude and
578 longitudes for fishing location, homeport names, province, vessel type, vessel
579 identification, landings, day of year sailed, week fished, and effort. There were a total of
580 86 homeports included in the dataset from four Canadian provinces; Québec, New
581 Brunswick, Nova Scotia and Prince Edward Island (Figure 2.1). This zone is the largest
582 in terms of area, amount of fishing vessels, permits, and snow crab landings (DFO 2016,
583 Gillis et al. 2006). Each zone has its own management strategy, and zone 12 manages the
584 fishery by implementing the following strategies; not allowing females to be fished, only
585 allowing crabs with a carapace width of ≥ 95 mm to be landed, the amount of licenses

586 distributed each year and allowing a certain total allowable catch set by individual fishing
587 quotas (Pinfold 2006, Siddeek et al. 2008, DFO 2016).

588 The vessels fishing in zone 12 can be classified into three groups: traditional, non-
589 traditional and First Nations vessels. As previously mentioned the traditional vessels fish
590 each year and have decades of experience. Non-traditional vessels generally do not fish
591 every year, although they may fish for consecutive years if they do not return to the
592 lobster fishery.

593 The fishery runs from spring to early summer each year and quotas are generally
594 met after 10-12 weeks of fishing (Charles et al. 2014). After the fishery closes for the
595 season, DFO performs their annual pre-season survey (DFO 2016, E. Wade, Gulf
596 Fisheries Centre DFO, Moncton, Canada, personal communication, 2016) to measure the
597 total amount of available snow crab biomass available to the fishery for the next fishing
598 season. They also create an abundance map using kriging with external drift (a
599 geostatistical technique) (Webster and Oliver 2001) using depth as a secondary variable
600 (Wade et al. 2014) for each grid and give this abundance information to all the fishers for
601 the upcoming season (E. Wade, Gulf Fisheries Centre DFO, Moncton, Canada, personal
602 communication, 2016). Since snow crabs on average do not travel large distances, this
603 gives the fishers information on the productive fishing areas (Biron et al. 2008) and
604 vessels with more experienced crews may be able to use additional knowledge (such as
605 bathymetry, where exactly in the grid to fish, or what depth to fish at) to fish even more
606 effectively.

607 **Data Preparation**

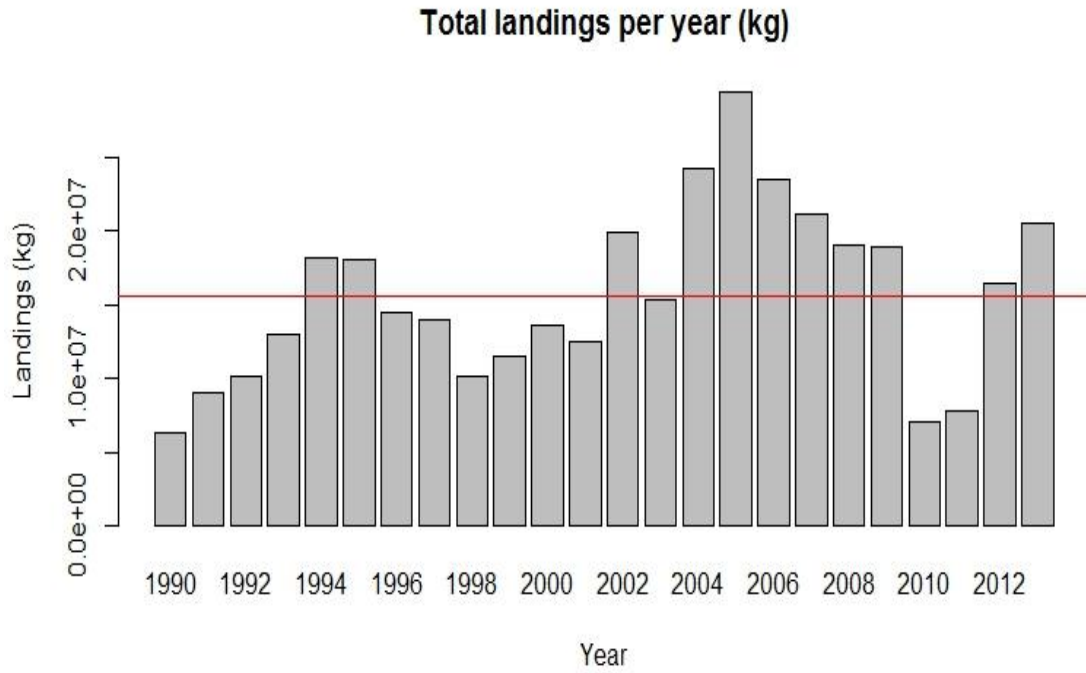
608 Two datasets were analysed; full and focus homeport datasets. The full dataset
609 encompasses all the data gathered from DFO while the focus homeport dataset is a subset
610 of the full, but focuses on the 9 major homeports (Figure 2.1) that represent 62% of the
611 total catch across the years. The full dataset was used to have a broader overview of the
612 fishery and then compare it to the focus homeport dataset, which examined a more
613 precise, higher activity portion of the fishery.

614 The dataset gathered by DFO had information on each vessel's homeport name
615 but lacked their coordinates, therefore the geographical coordinates of the homeports
616 were taken from MarineTraffic (2017). The datasets fishing location coordinates (latitude
617 and longitude) were in decimal degrees so the homeport coordinates were converted into
618 decimal degrees. Each vessel's identity was kept confidential through randomly assigned
619 vessel identification numbers (VID).

620 The full dataset had 86 homeports, spread out across Québec, New Brunswick,
621 Prince Edward Island and Nova Scotia (Figure 2.1). The full dataset was used in analysis
622 to examine homeport location impacts on associations and vessel type interactions. The
623 focus homeport dataset examined the homeports (Figure 2.1) that had a minimum of 50
624 vessels fishing each year, which represented a total of 62% of zone 12's catch. This
625 subset contained four homeports from Québec: St-Therese-de-Gaspe, Grande-Riviere,
626 Newport Point and Gascons. There were three in northern New Brunswick: Caraquet,
627 Lameque, and Shippagan, and two in southern New Brunswick: Richibucto and Big
628 Cove.

629 The number of vessels and types of vessels fishing per year varied (Figure 2.2) and their
630 resulting catch rates or landings as well (Figure 2.3) and therefore the years included in
631 the analysis varied as well. The full dataset covered different years in the Mantel and
632 Ripley's K analysis. The years in the Mantel test were 1990 through 2013, while in
633 Ripley's K, the years were 1995-97, 2000-13. The reason behind these differences was
634 that there was always a minimum of 10 vessels fishing in each year so the Mantel test
635 analysis included the full range of years. In Ripley's K analysis there needed to be at least
636 three unique vessels of each type fishing per year, so the range of years is limited in the
637 Ripley's K analysis. The focus dataset looked at the main 9 homeports and only had data
638 from 2001-2013, and had enough vessels and types for all those years for both the Mantel
639 tests and Ripley's K analysis.

640 Vessel data were subsampled from two-week periods (fortnight) to reduce serial-
641 autocorrelation and provide a more even representation of the analysed data. Fortnight of
642 year (FOY) was set up as two-week periods starting from January 1st until the last day of
643 the fishery for any given year ranging from 9-16. The first trip made by each vessel
644 during a fortnight was kept for analysis. Some vessels only had a single trip while some
645 had multiple, so this dealt with the autocorrelation of similar fishing trips as well as not
646 over-representing a vessel. Also the middle FOY of the season was kept for each analysis
647 to represent when the most vessels were fishing, and giving the vessels enough time to
648 react to the information shared or gathered. It was thought that at the beginning of the
649 fishery not all vessels have begun fishing and they have not gathered their own
650 experience to communicate yet, and similarly at the end of the season not all vessels are
651 fishing as most quotas have been met and fishable snow crab are less abundant.



653 **Figure 2.3 Landings in kilograms of the Gulf of St. Lawrence snow crab fishery in**
 654 **zone 12 from 1990-2013. Landings were obtained from DFO yearly surveys. The red**
 655 **line indicates the average catch from 1990-2013 and is my threshold for high (above**
 656 **line) landings and low (below line) landings used in the analysis.**

657

658 *Section 2.1- Vessel associations based on homeport location*

659 To test the hypothesis that vessels from similar or close homeports would be
660 clustered together on the water while fishing, a Mantel test (Mantel 1967) was performed
661 on both the full and focus homeport datasets. Mantel tests determine whether there is
662 significant correlation between the two locations or coordinates in question by testing
663 against the null hypothesis of a random distribution (Sokal 1979, Oden and Sokal 1986,
664 Smouse et al. 1986, Legendre and Fortin 1989). The only assumption that restricts a
665 Mantel test is that the matrices must be independent from each other. In other words, one
666 matrix may not be derived from the information of the other (Legendre and Fortin 1989,
667 Legendre and Fortin 2010). To have a precise comparison, fortnights with a minimum of
668 ten vessels fishing were used, although generally this was not an issue except in the first
669 and last fortnights of some years and is why the middle FOY were chosen as discussed
670 previously.

671 The Mantel test uses two distance matrices to test for spatial correlation. In this
672 analysis the homeport and fishing coordinates were used to create these matrices using
673 Universal Transverse Mercator (UTM) coordinates and the distances between the
674 matrices were then calculated. They were then analysed using the ade4 (Dray and
675 Dufour 2007) package in R (R Core Team 2015) and a correlogram was done using the
676 vegan package (Oksanen et al. 2017). The Mantel tests were performed with 1000
677 permutations ($\alpha = 0.05$) using a Pearson correlation (Legendre and Fortin 2010). For each
678 year (1995-97, 2000-13 for full dataset, and 2001-13 for focus dataset), the middle FOY
679 was used for the final analysis to represent the busiest fishing weeks by looking at the
680 starting and ending FOY of the season and choosing the FOY in the middle. Differences

681 between FOY were expected. During the first and last FOY not every vessel is fishing.
682 During the early fortnights the vessels haven't been fishing for long, which may suggest
683 there is less private information to share, but more current public information from the
684 previous DFO survey. A correlogram was created for each of these middle FOY across
685 all the years to plot the changing values across increasing distances (5, 10, 15, and 20
686 km). These distances were chosen since the crew of these vessels can see approximately
687 20 km under ideal conditions while at sea (Bowditch 2002, Gillis et al. 2006).

688 *Section 2.2- Associations based on vessel type*

689 To test the hypothesis that vessel type impacts how vessels associate, Ripley's K
690 function was used. The full and focus homeport datasets were analysed using Ripley's K
691 function to examine spatial point patterns for evidence of aggregation based on vessel
692 type (Cox and Lewis 1972, Van Lieshout and Baddeley 1999). The vessel's fishing
693 coordinates (in decimal degrees for latitude and longitude) were transformed into
694 Universal Transverse Mercator (UTM) coordinates, to create a spatial point pattern
695 matrix in Cartesian coordinates and for consistency as it was done in the Mantel tests.

696 The middle FOY of the fishing season was again chosen for each season to
697 represent when the most vessels were fishing. Analysis was done only if there were at
698 least three different vessels of each type, which eliminated 1990-1994 and 1998-2000.
699 There were always fewer non-traditional vessels fishing compared to traditional vessels
700 (Figure 2.2).

701 Associations between and within vessel types were examined using the K_{cross} and
702 K_{est} functions respectively in the spatstat package (Dixon 2002) in R (R Core team 2015)

703 across the four distances chosen (5, 10, 15, 20 km). The equation for the K_{est} function is
704 (Dixon 2002):

705 2.1
$$K_{ii}(t) = \lambda_i^{-1}E$$

706 Where i represents the single event type (in this case a unique vessel type), λ is the the
707 density (number per unit area of events and E represents the number of extra events
708 within a distance t of a randomly chosen event). K_{est} is used to look at a single type or
709 observation in this case each vessel type as similar individuals. To examine spatial
710 patterns between traditional and non-traditional, K_{cross} is applicable to multivariate
711 spatial point patterns and is developed from the K_{est} function but is generalized (Dixon
712 2002) as:

713 2.2
$$K_{ij}(t) = \lambda_{ij}^{-1}E$$

714 where j represents an other unique event type (in this case to compare the two unique
715 vessel types, traditional and non-traditional) but $i \neq j$, and the $K_{ij}(t)$ function is similar
716 to the estimators of the univariate $K_{ij}(t)$ function but examines more event types or
717 different types of species for spatial associations and E is the number of type j events
718 within a distance t of a randomly chosen type i event. To test the model at a significance
719 level of $\alpha=0.05$, and 1000 simulations (Baddeley and Turner 2005, Dixon 1994, Dixon
720 2012) were done using a confidence envelope around the H_0 (null) of complete spatial
721 randomness (CSR). A standardized distance was created by calculating the distance from
722 the K value to the top or bottom of the envelope minus the theoretical random value to
723 visually observe whether the K value was clustered, random, or dispersed. The top of the
724 envelope was used if the K value was above the envelope and the bottom if it was below
725 the envelope.

726 *Section 2.3- Vessel impacts on snow crab population*

727 In fisheries, a common way to model catch in relation to effort of the vessels and
728 abundance of the fish (Maunder and Punt 2004) is

729 2.3
$$C = qfN$$

730 where C is the catch rate, q is a catch constant, f is the effort applied, and N is the
731 abundance of the targeted fished and when rearranged represents CPUE (C/f) which is
732 proportional to the abundance of the targeted species, and the foundation for the additive
733 mixed model to look at the behavioural interactions between fishing vessels and impacts
734 on snow crab mortality. Equation 2.3 applies when the underlying relationships are
735 proportional. When the relationship is non-linear then the equation is

736 2.4
$$C = q f^\beta N^\gamma$$

737 where the exponents β and γ represent the estimate of the linear predictor N from a
738 generalized linear model. This relationship can be expanded into an additive mixed
739 model (AMM) with additional predictors for other influences on catch beyond nominal
740 effort :

741 2.5
$$Y_i = \mathbf{X}_i \boldsymbol{\theta} + f_1(x_{1i}) + \dots + \mathbf{Z}_i \mathbf{b} + \varepsilon_i$$

742 where Y_i represents the i^{th} observation, \mathbf{X}_i is the i^{th} row of the fixed effect model matrix, $\boldsymbol{\theta}$
743 is a vector of fixed effect coefficients, $f(\cdot)$ represents smooth functions of the covariate x ,
744 \mathbf{Z}_i is a row of a random effects model matrix while $\mathbf{b} \sim N(0, \psi)$ is a vector of random
745 effects coefficients with unknown positive covariance matrix ψ , while ε_i represents the
746 residual error (Wood 2006). The response variable for this section was logged catch in kg
747 and is represented by Y_i in equation 2.5. The distribution of catch was skewed to the left
748 but when log transformed appeared to have a lognormal distribution after plotting it

749 (Quinn and Keough 2002). Therefore a Gaussian distribution with a log link was used
750 (Zuur 2012). The response predictors used to look for trends in catch rates were year and
751 day of year (DOY) fished, which were smoothed using thin plate regression splines
752 (Wood 2006) to reduce the number of estimated parameters (2001-2013 for year, 120-
753 150 days for DOY). Homeport, vessel type and logged effort per day were treated as
754 fixed effects. Each vessel has a different crew with varying amounts of experience and
755 knowledge and each vessel differs in terms of make, tonnage, length, speed etc., therefore
756 VID was treated as the random effect to account for the individual variation amongst
757 vessels that is not measurable, but influences the response variable, logged catch. The
758 equation of the resulting additive mixed model is

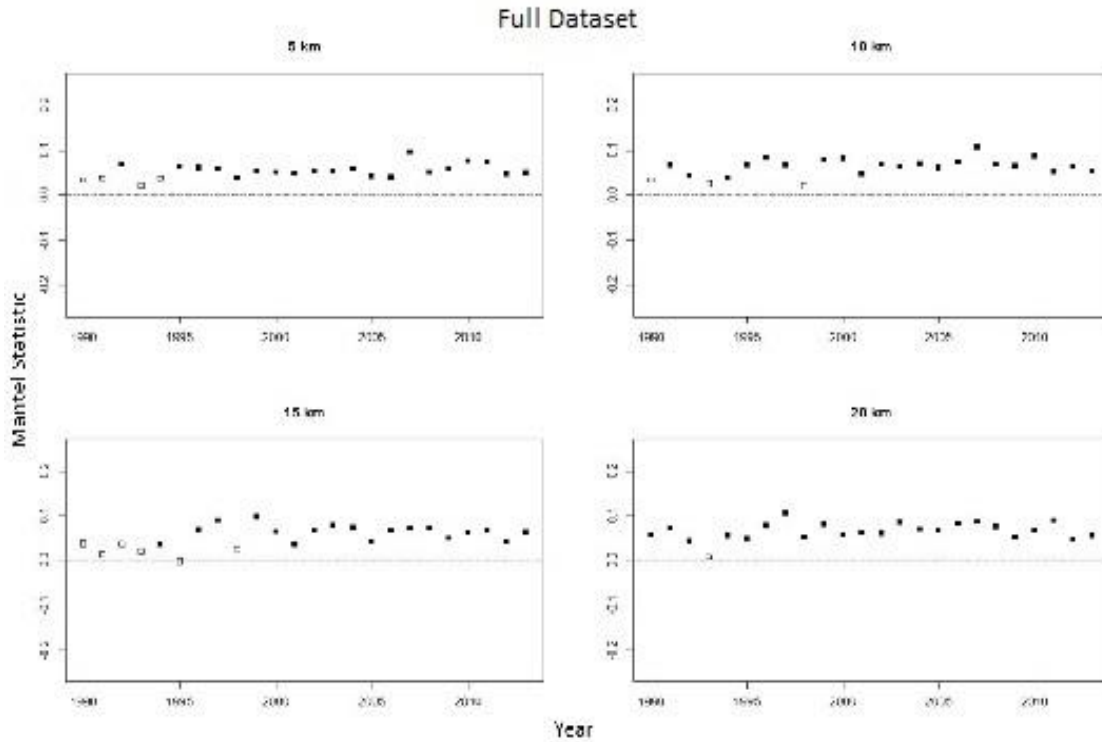
$$759 \quad 2.6 \quad \log(\text{catch}) = s(\text{year}) + s(\text{DOY fished}) + \beta_1 * \text{homeport} \\ 760 \quad \quad \quad + \beta_2 * \text{status} + \beta_3 * \log(\text{effort}) + VID_i + \varepsilon_i$$

761 For the full dataset it was difficult to converge to a solution using an additive
762 mixed model (AMM) so only the focus homeport dataset was used. Trying to get
763 convergence around 24 years, at 86 homeports with varying levels of vessels (ranging
764 from zero to several hundred) and hundreds of days fished was preventing the
765 convergence of the full dataset. Therefore, I chose to develop the model using data from
766 homeports that fished more consistently through the period studied (the focus dataset) to
767 get a representative model for the Gulf of St. Lawrence snow crab fishery.

768 **Results**

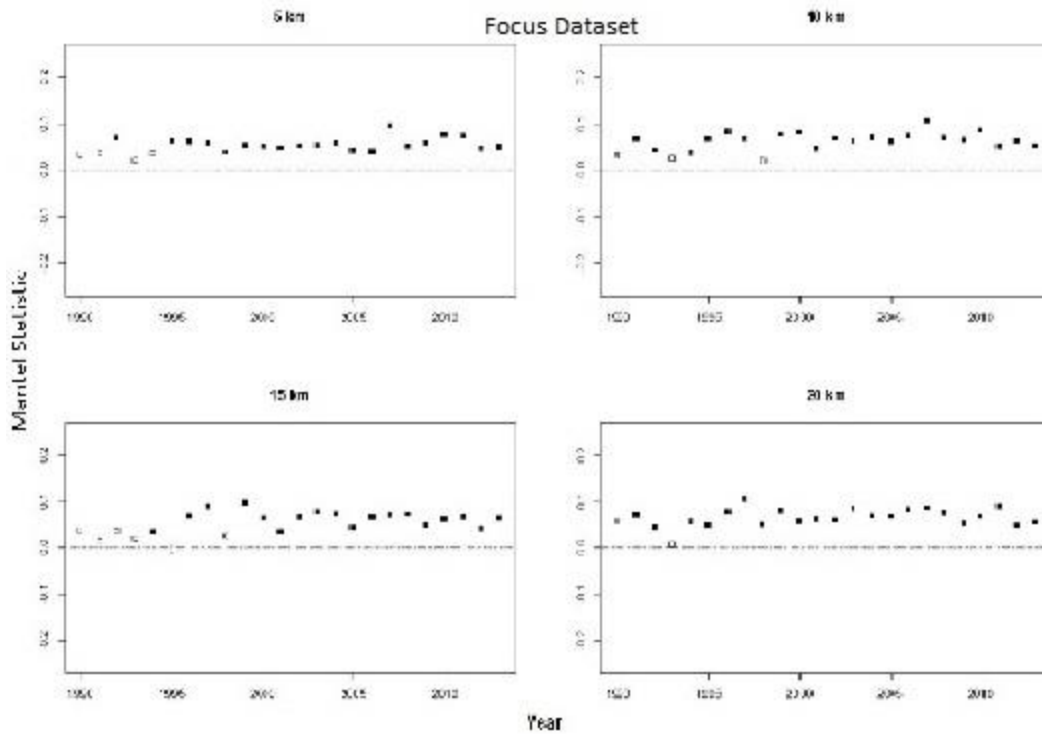
769 *Section 2.1- Vessel associations based on homeport location*

770 Both results from the full and focus homeport (Figure 2.4 A and B and Figure 2.5)
771 datasets support the hypothesis that vessels from similar homeports are clustering on the



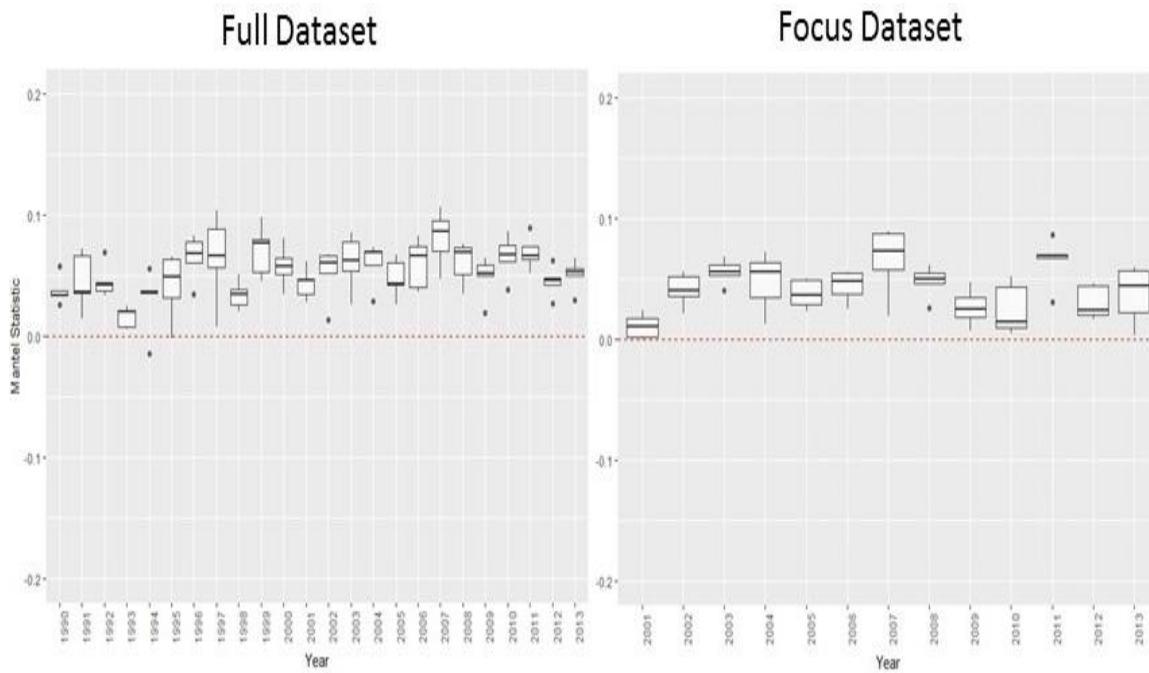
772 **Figure 2.4 A) Using a correlogram to plot the results from Mantel test looking at**
 773 **four distances (5, 10, 15, and 20 km) from 1990-2013 using the full dataset. A**
 774 **negative value indicates dispersion and a positive is clustering of vessels. Zero**
 775 **represents a random distribution. Testing alpha=0.05. Black squares represent**
 776 **significant values while the white ones are insignificant. The dashed line represents**
 777 **the Ho: of a random distribution.**

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788 **Figure 2.4 B) Using a correlogram to plot the results from Mantel test looking at**
 789 **four distances (5, 10, 15, and 20 km) from 1990-2013 using the focus dataset. A**
 790 **negative value indicates dispersion and a positive is clustering of vessels. Zero**
 791 **represents a random distribution. Testing alpha=0.05. Black squares represent**
 792 **significant values while the white ones are insignificant. The dashed line represents**
 793 **the Ho: of a random distribution.**

794



795 **Figure 2.5** A boxplot representing the Mantel statistics across the years including all
 796 **four distance classes analysed (5, 10, 15 and 20 km) for both the Full and Focus**
 797 **datasets of the statistic values in each year.**

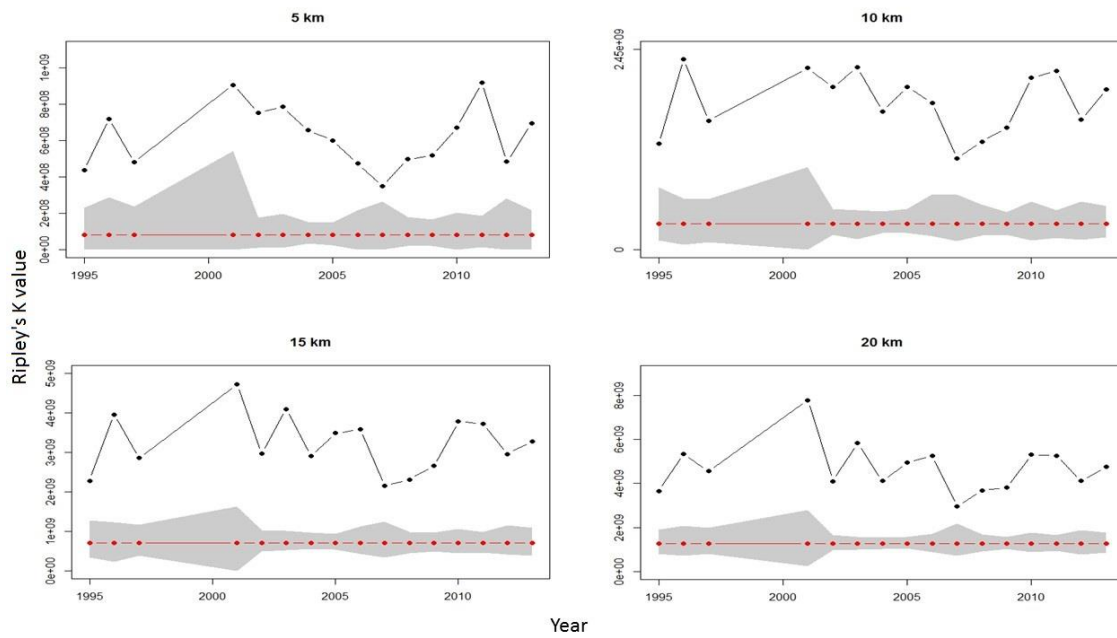
798

799 water while fishing, although the tendency is not strong. The correlogram at all distances
800 for the full dataset shows a weak positive correlation between homeport location and
801 fishing locations that is significantly non-random in most years. The focus homeport
802 dataset has similar weak positive correlations across most of the years and distances
803 (Figure 2.4 B and Figure 2.5).

804 *Section 2.2- Associations based on vessel type*

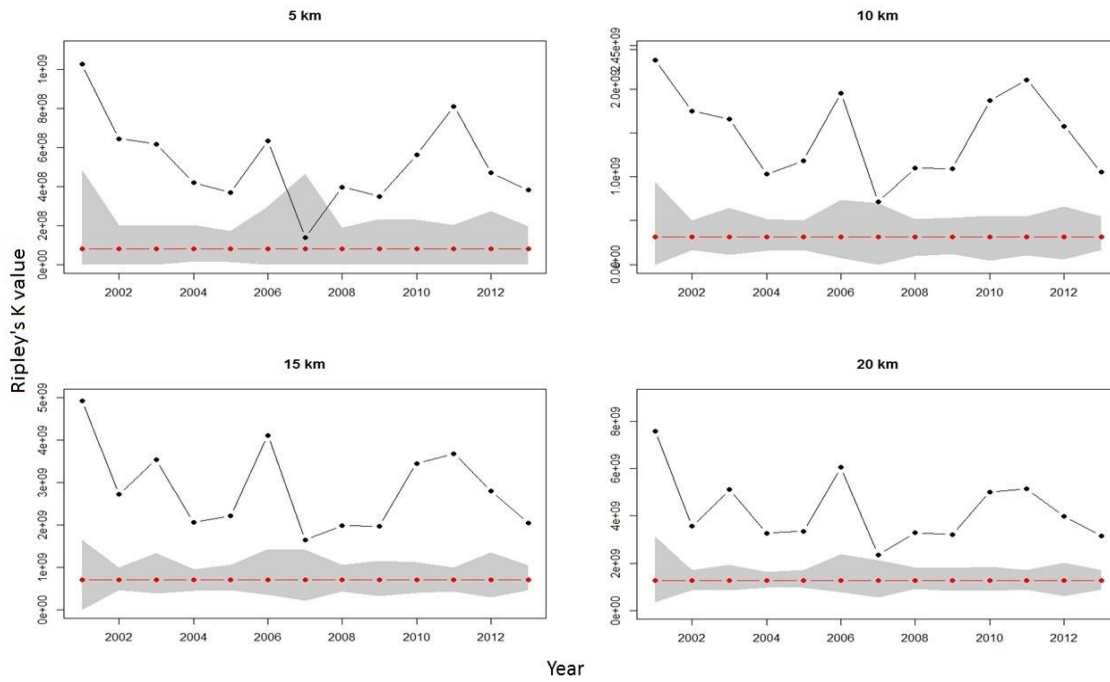
805 *Traditional and other traditional vessels*

806 Traditional vessels displayed aggregation amongst themselves in both the full
807 (Figure 2.6) and focus homeport datasets (Figure 2.7) when analysed using Ripley's K
808 function. Each of the studied years show significant spatial clustering across all four
809 distances in both datasets. There are some peaks and troughs in the levels of clustering in
810 certain years which correspond to general patterns in snow crab landing rates (Figure
811 2.3). There was a peak in clustering observed in 2001, which corresponded to a lower
812 snow crab landing year. The next trough was seen in 2010-11 and there was a peak in
813 clustering again. Around 2005-07 there was an abundance of snow crabs resulting in
814 higher landings, and lower levels of spatial clustering were observed amongst the
815 traditional vessels (Figure 2.8). In Figure 2.8 the standardized level of association for
816 Ripley's K (standardized distance in figures) was used to visually observe whether the K
817 value was clustered, random or dispersed across the years for the three types of
818 associations and the extent, showing that traditional vessels always had higher levels of
819 clustering. The clustering between the two types was lower, and the non-traditionals were
820 lower and closer to random. There were higher landings in 1994-95, 2004-06, 2013 and
821 lower landings in 1990, 1998, and 2010-11 (Figure 2.8).



823 **Figure 2.6** The results of the full dataset from 1995-2013 of Ripley's K estimate. This
 824 **graph looks at associations among traditional vessels. The grey area shows the**
 825 **confidence envelope around Ho of a random distribution. Within the grey area**
 826 **cannot be distinguished from a random distribution. The red dashed line is the**
 827 **theoretical values of random distribution for the data (Ho hypothesis). Anything**
 828 **above is significantly clustered while below is significantly dispersed.**

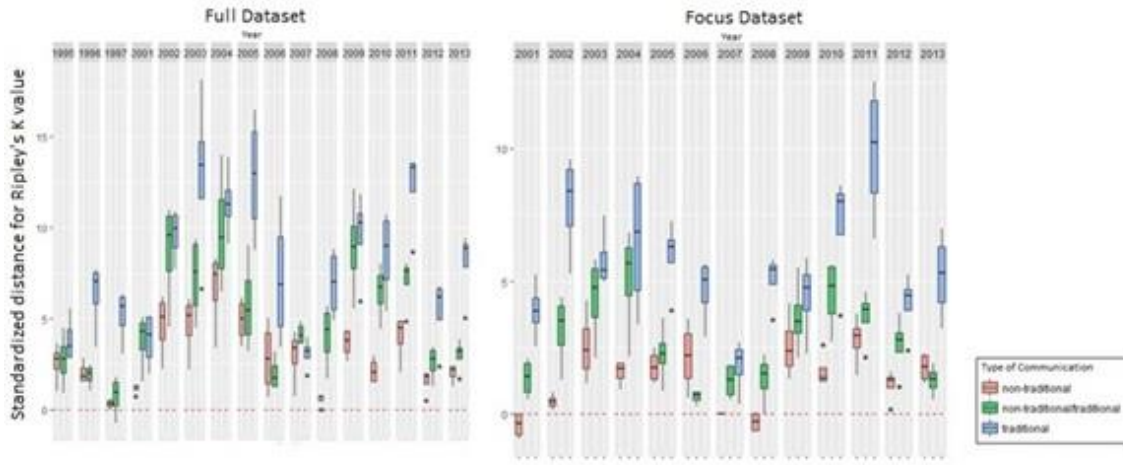
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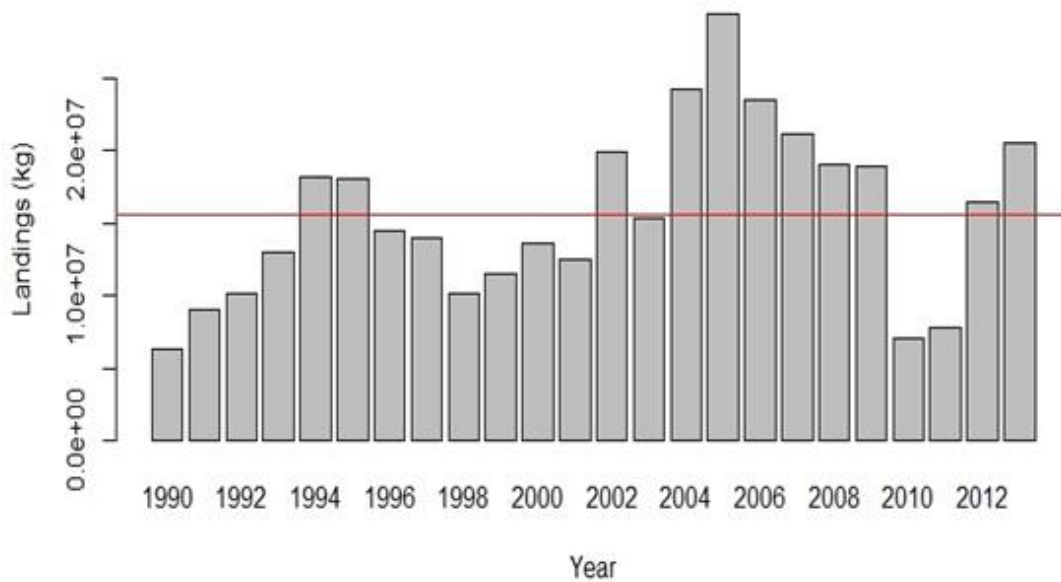
830

831 **Figure 2.7 Ripley's K estimates from the focus homeport dataset looking at the**
 832 **associations among the traditional vessels. The grey area shows the confidence**
 833 **envelope around Ho of a random distribution. Within the grey area cannot be**
 834 **distinguished from a random distribution. The red dashed line is the theoretical**
 835 **values of random distribution for the data (Ho hypothesis). Anything above is**
 836 **significantly clustered while below is significantly dispersed.**

837



Total landings per year (kg)



838 **Figure 2.8** A boxplot of Ripley's K standardized distance values for the full and
 839 **focus datasets and the landings of those years to examine spatial associations across**
 840 **the high and low landing years.**

841

842

843

844 *Non-traditional and other non-traditional vessels*

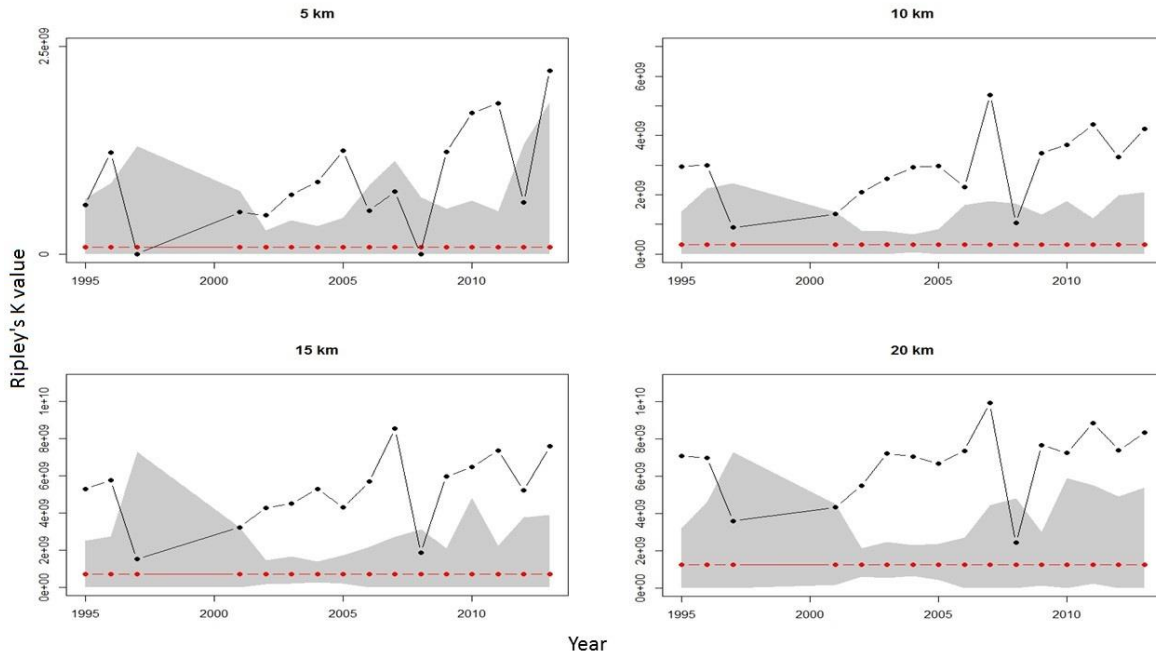
845 The spatial associations among non-traditional vessels differed from that of the
846 traditional vessels (Figure 2.9 and Figure 2.10). The results for the non-traditional vessels
847 varied, there was a general random distribution pattern, although there was clustering in
848 some years. During seven years (out of 16 total years) at 5 km there was mostly complete

849 *Non-traditional and other non-traditional vessels*

850 The spatial associations among non-traditional vessels differed from that of the
851 traditional vessels (Figure 2.9 and Figure 2.10). The results for the non-traditional vessels
852 varied, there was a general random distribution pattern, although there was clustering in
853 some years. During seven years (out of 16 total years) at 5 km there was mostly complete
854 clustering. The clustering between the two types was lower, and the non-traditionals were
855 lower and closer to random. There were higher landings in 1994-95, 2004-06, 2013 and
856 lower landings in 1990, 1998, and 2010-11 (Figure 2.8).

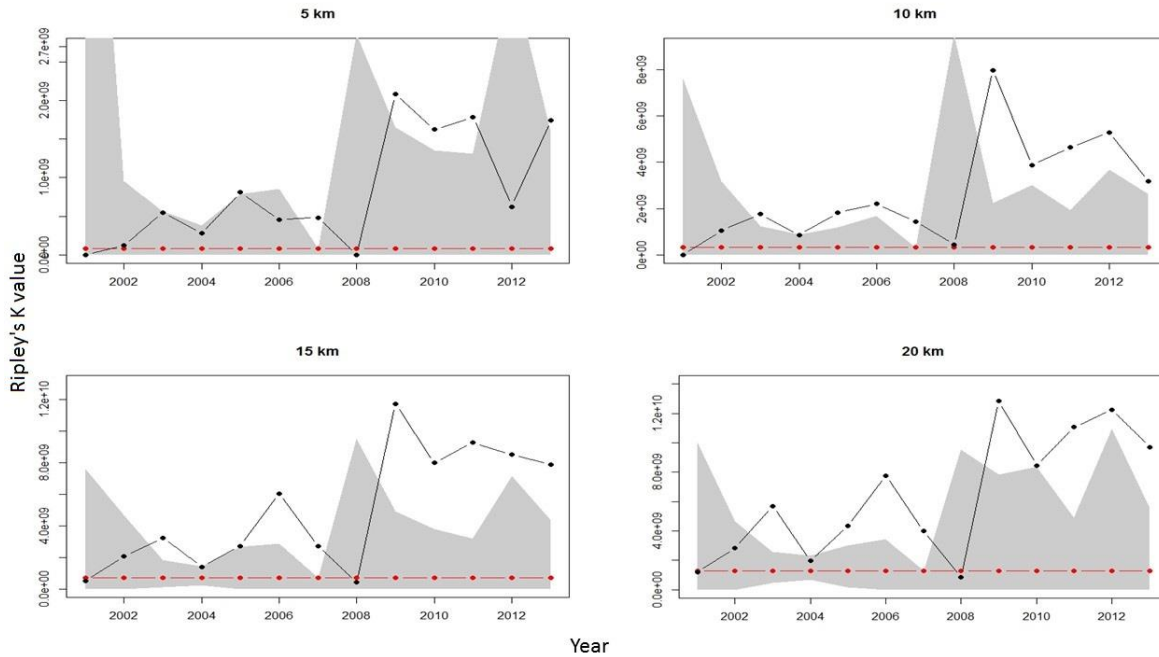
857 *Non-traditional and other non-traditional vessels*

858 The spatial associations among non-traditional vessels differed from that of the
859 traditional vessels (Figure 2.9 and Figure 2.10). The results for the non-traditional vessels
860 varied, there was a general random distribution pattern, although there was clustering in
861 some years. During seven years (out of 16 total years) at 5 km there was mostly complete



862 **Figure 2.9 Ripley's K value estimates from the full dataset across four distances (5,**
 863 **10, 15, 20 km) the results among non-traditional vessels. The grey area shows the**
 864 **confidence envelope around Ho of a random distribution. Within the grey area**
 865 **cannot be distinguished from a random distribution. The red dashed line is the**
 866 **theoretical values of random distribution for the data (Ho hypothesis). Anything**
 867 **above is significantly clustered while below is significantly dispersed.**

868



869 **Figure 2.10** The results from the focus homeport dataset for Ripley's K estimate
 870 among the non-traditional vessels. The grey area shows the confidence envelope
 871 around Ho of a random distribution. Within the grey area cannot be distinguished
 872 from a random distribution. The red dashed line is the theoretical values of random
 873 distribution for the data (Ho hypothesis). Anything above is significantly clustered
 874 while below is significantly dispersed.

875

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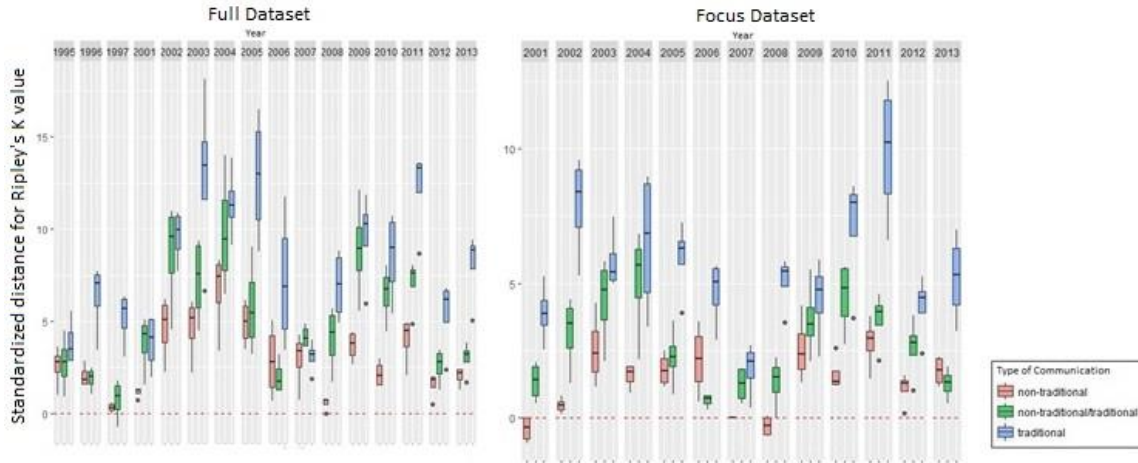
877 spatial randomness in the full dataset (Figure 2.9). In the focus dataset at 5 km there were
878 also seven years (out of a total of 13) where patterns of aggregation did not depart from
879 spatial randomness, although the years of clustering observed were not far from
880 randomness (Figure 2.10). As distance increased, there was more clustering observed.
881 When there was clustering it wasn't as strong as for the traditional vessels (Figure 2.11).

882 *Non-traditional and traditional vessels*

883 There was a general clustering observed between the two types of vessels in both
884 the full (Figure 2.12) and focus homeport (Figure 2.13) datasets. In the years 2000-01,
885 2010-11 there were lower landings with a peak seen in the level of clustering in both
886 datasets. There were increased landings from 2004-2006 and this corresponded to spatial
887 randomness or lower levels of clustering in both datasets similar to the single vessel type
888 results (Figure 2.11).

889 *Section 2.3- Vessel type impacts on catch rate*

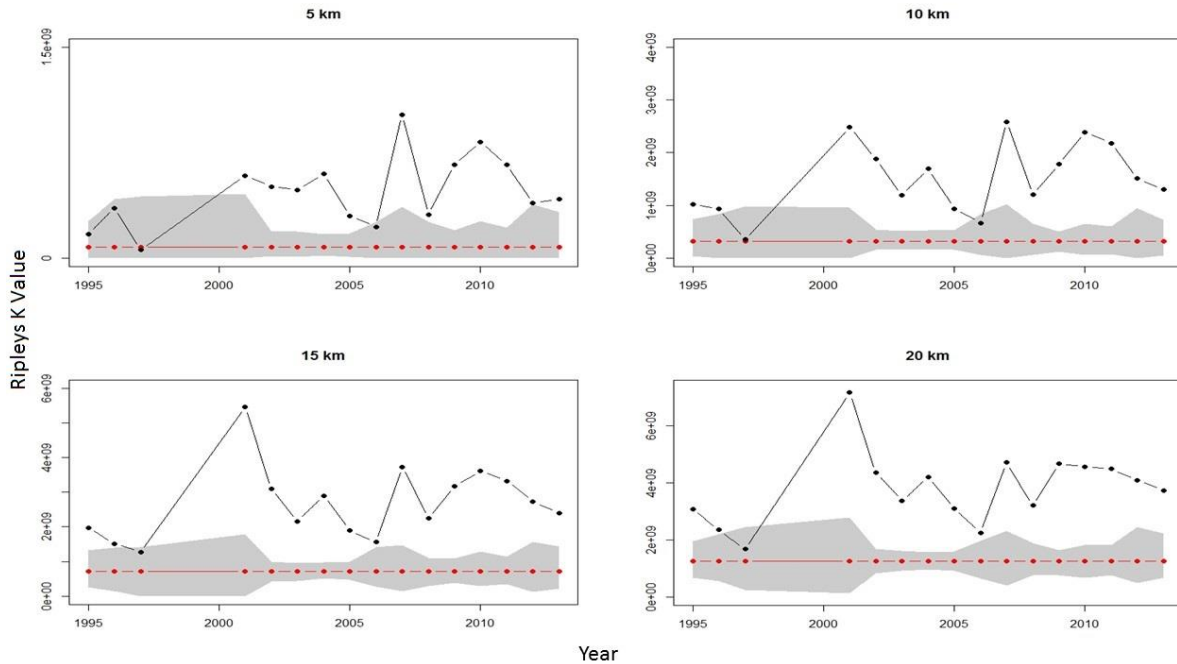
890 The focus homeport dataset was examined with an AMM (Table 2.1). The model
891 was set up with a traditional vessel from Shippagan as the reference case (intercept) for
892 comparison amongst the other predictors. Shippagan is one of the original homeports
893 with the most vessels and since there were only two types of vessels in the analysis, a
894 traditional vessel was used as they are the vessels with crews who know the fishery the
895 best and would have been the original vessels of the fishery. Model selection was
896 performed using maximum likelihood to see whether homeport was significant or not and
897 the model including homeports had a greater likelihood ratio test value (20.5), higher
898 degrees of freedom (18 for full model and 10 without homeports), with a p-value of
899 0.008. The final model was re-estimated using restricted maximum likelihood to obtain



900 **Figure 2.11** Boxplots of Ripley's K values for the full and focus dataset. A
 901 standardized distance was calculated by (the estimated K value / (top or bottom of
 902 envelope – theoretical random value)) to create a standardized level of association
 903 for Ripley's K. The top of the envelope was used if the K value was above the
 904 envelope (clustered), or the bottom if there was dispersal. 0 was used to represent
 905 random distribution (within the envelope). All three vessel type associations were
 906 plotted across the years at all four distances classes (5, 10, 15, 20 km). The boxplots
 907 represent the interquartile range (box) and 95% range (whiskers) of the K values.

908

909

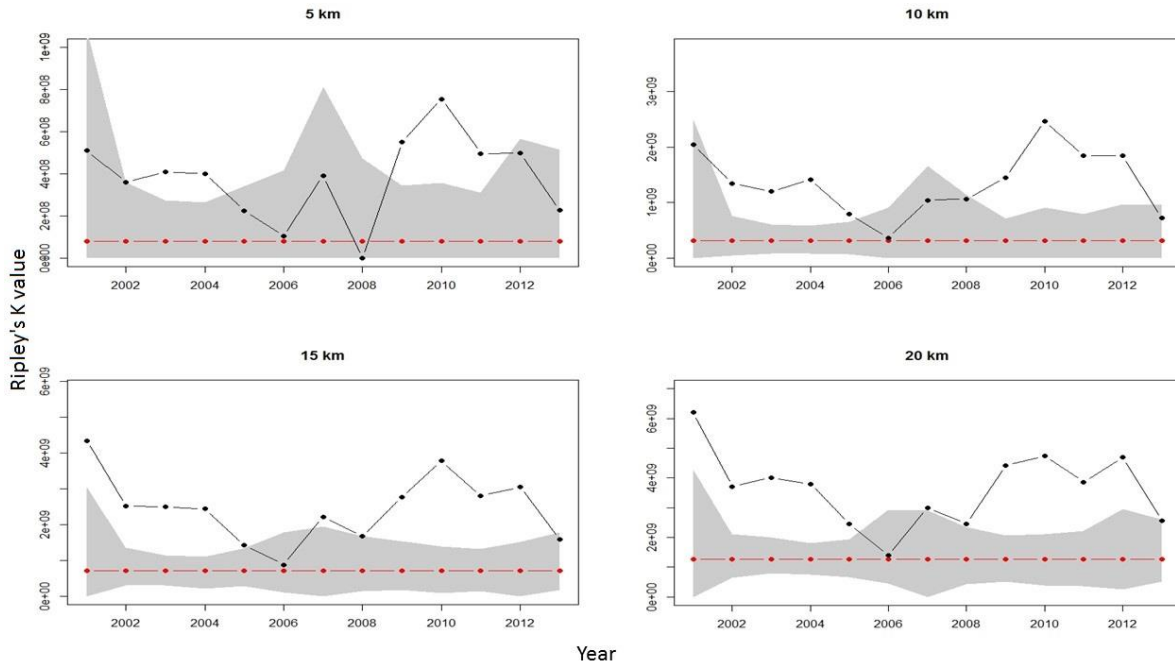


910 **Figure 2.12 Ripley's K estimates of the full dataset examining clustering between**
 911 **traditional and non-traditional vessels. The grey area shows the confidence envelope**
 912 **around Ho of a random distribution. Within the grey area cannot be distinguished**
 913 **from a random distribution. The red dashed line is the theoretical values of random**
 914 **distribution for the data (Ho hypothesis). Anything above is significantly clustered**
 915 **while below is significantly dispersed.**

916

917

918



919 **Figure 2.13 Ripley's K estimates of the focus homeport dataset for the non-**
 920 **traditional to traditional vessels. The grey area shows the confidence envelope**
 921 **around Ho of a random distribution. Within the grey area cannot be distinguished**
 922 **from a random distribution. The red dashed line is the theoretical values of random**
 923 **distribution for the data (Ho hypothesis). Anything above is significantly clustered**
 924 **while below is significantly dispersed.**

925

926

927 **Table 2.1 Results from the AMM model estimating trends in catch rates. The**
 928 **intercept is a non-traditional vessel from Shippagan. The smoothed terms (year and**
 929 **day of year fished) are seen below. The $R^2 = 0.649$, $n=32560$. The overall effect of**
 930 **homeport was tested using a likelihood ratio test, and when compared to a reduced**
 931 **model without homeport.**

Province	Parametric coefficients	Estimate	Standard Error	t value	Pr(> t)
NB	Intercept	3.84	0.04	109.07	<0.001
NB	homeport Lameque	-0.01	0.04	-0.18	0.88
NB	homeport Caraquet	0.08	0.05	1.67	0.09
NB	homeport Richibucto	-0.03	0.07	-0.46	0.66
NB	homeport Big Cove	-0.11	0.05	-2.05	0.04
QC	homeport Gascons	-0.06	0.07	-0.75	0.45
QC	homeport Grande-Riviere	-0.12	0.07	-1.80	0.08
QC	homeport Newport Point	-0.14	0.05	-2.54	0.01
QC	homeport Ste-Therese-de-Gaspe	-0.05	0.05	-0.97	0.32
	status Non-Traditional	-0.14	0.03	4.42	<0.001
	log(fishing traps/day)	1.01	0.01	188.74	< 0.001

932 Smooth terms:

	edf	Ref.df	f	p-value
s(year)	8.75	8.75	242.8	<0.001
s(DOY.fished)	6.31	6.31	289.2	<0.001

933

934 Random Effect (VID):

Lower	Est.	Upper
83.62	279.66	922.60

935

936

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939

940 unbiased parameter estimates. The final model used a base case (intercept value) of a
941 traditional vessel from Shippagan using homeports as a variable. When the other
942 homeports were compared to Shippagan, only Big Cove ($p=0.04$) and Newport Point
943 ($p=0.01$) were significantly different from Shippagan but had slightly lower catches.
944 Traditional vessels had higher catches than the non-traditional vessels. With effort and
945 catch being logged the results revealed that effort was proportional to catch as the slope
946 could not be statistically distinguished from one.

947 The smooth terms of the AMM (Figure 2.14) represent the impacts of year and
948 day of year fished on catch rates. Year was influential on catch rates ($p= <0.001$ from
949 Table 2.1) and showed varying trends across the different years. In the years from 2004-
950 2006 there were increased landings (Figure 2.3). In 2001 and again from 2010-11 there
951 were lower landings. The day of year fished is also influential on catch rates ($p= <0.001$
952 Table 2.1) as fishing earlier in the season corresponded to higher catch rates that
953 subsequently declined throughout the duration of the season (Figure 2.14)

954

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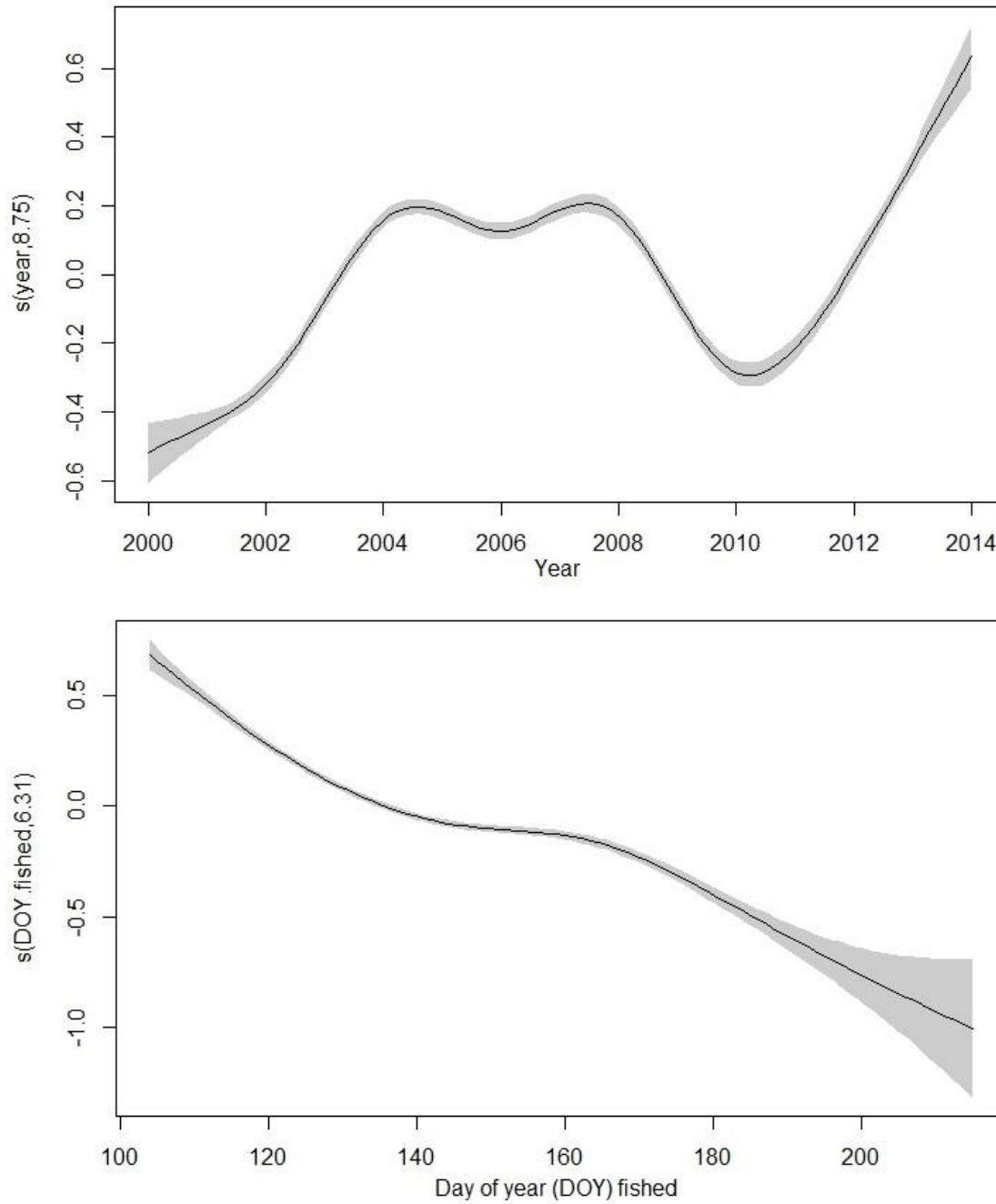
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962 **Figure 2.14** The smoothed predictors (with the degrees of freedom in the brackets)
 963 of the additive mixed model are year, and day of year (DOY) fished.

964

965 **Discussion**

966 Overall the results supported the hypotheses, as there was clustering observed amongst
967 traditional vessels, random distributions between non-traditional vessels, clustering
968 amongst the two types of vessels, and minimal clustering of vessels from similar
969 homeports. Traditional vessels may benefit from communicating their information, as it
970 would reduce the time they spend searching for high abundance areas (Branch et al.
971 2006). They would likely be more willing to help out their friends and family, resulting in
972 clustering of many successful vessels. Since the number of vessels of each type varies
973 across years, it was important to analyse how these vessels use the information given to
974 them and where they fish. A tendency to aggregate may increase local crab exploitation
975 beyond that expected from fishing alone, especially if vessels entering the fishery follow
976 more experienced vessels rather than exploring independently. In a year of increased
977 vessel licenses this could result in even more vessels clustering in an area, and in turn
978 impact the snow crab population at these overfished locations. The clustering of
979 traditional vessels could be the result of their communication, or from their experience in
980 the fishery. The traditional vessels have been fishing for decades and likely know each
981 other. Although some of these vessels have been fishing since the 1960's so even if there
982 is no communication, these vessels may just be more successful at using survey data and
983 their own experiences to locate fish.

984 Results suggest that non-traditionals tend to have a random distribution amongst
985 themselves. There were lower levels of clustering between non-traditional vessels at
986 smaller distances but clustering was observed at higher distances, which could be the
987 result from their associations with traditional vessels or results of coarse-level local

988 enhancement (Pöysä 1992). Traditional vessels had significantly higher catch rates than
989 the non-traditional vessels and since non-traditional vessels have less experience in the
990 fishery, they are less likely to follow another non-traditional vessel. This may not be the
991 case if multiple non-traditional vessels are following a single traditional vessel. This
992 would result in clustering of non-traditional vessels even though the clustering could be
993 due to the non-traditionals fishing in a similar area as a traditional vessel. This could
994 explain the non-traditional clustering at larger distances classes.

995 In that traditional vessels have permanent allocations in the fishery their
996 investment may differ from the non-traditionals (Branch et al. 2006). Traditional vessels
997 may be more inclined to protect the fishery to maintain a long-term sustainable fishery.
998 They have permanent licenses so even though as a whole they have higher catches, at an
999 individual level, they may be catching less in lower abundance years to preserve the
1000 population and may be a factor to look into in the future of this fishery. They also have
1001 more licenses so could be making up the higher proportion of catch this way. Non-
1002 traditional vessels only come into the fishery when the lobster fishery is poor so are less
1003 invested in the fishery, looking for short-term higher gains rather than long-term
1004 sustainability in comparison to their counterparts. With them coming into the fishery
1005 sporadically, this may limit their knowledge of the fishery, and how to use the pre-season
1006 survey data effectively. This could explain them clustering around successful traditional
1007 vessels.

1008 The additive mixed model results indicate that Shippagan, Big Cove, and
1009 Newport Point have the highest catch rates in comparison to the other homeports, which
1010 also could be impacting which vessels are clustering as well, and could explain the lower

1011 levels of clustering seen amongst vessels from similar homeports. If only three out of the
1012 nine main homeports have the highest catch rates, the other lower landing homeports may
1013 have weaker incentives for aggregation.

1014 The associations varied across years and could be related to landing rates. When
1015 landings were higher there was generally less clustering between all the vessels, which
1016 could mean that there was less need to communicate. In lower landing years, where snow
1017 crab were not as abundant, there was more clustering of vessels, likely due to the
1018 increased use of information (both communication and observation) among the vessels to
1019 locate productive areas and meet individual quotas.

1020 The Gillis et al. (2006) study concluded that vessel types within homeports were
1021 clustering, which is a finer scale study. This study instead aimed to see whether vessel
1022 type or homeport location had higher influence on vessel's fishing location. The study
1023 concluded that there were low levels of clustering amongst vessels from similar
1024 homeports but coupled with the information about vessel type associations supports the
1025 findings of Gillis et al. (2006). It is likely that traditional vessels from the same homeport
1026 (i.e. Shippagan, Big Cove, or Newport Point) are the main driving force of clustering and
1027 not necessarily just homeport location or vessel type as individual factors. In other words
1028 not all traditional vessels and not every vessel from each homeport aggregate. These
1029 results are consistent with information exchange and it seems that traditional vessels are
1030 clustering in similar locations whether it is due to experience, verbal or visual
1031 communication, but their overall higher success rates may be impacting snow crab
1032 abundance. If non-traditional vessels are able to follow these successful traditional

1033 vessels then the local fishing pressure could exceed what would be expected when non-
1034 traditional vessels fished more independently.

1035 The significant predictors of catch rate in the additive mixed model were
1036 consistent with patterns of association in the spatial analysis. Temporal patterns in the
1037 smoothed terms of the additive mixed model indicate that catch rates varied within and
1038 between seasons, but with overall higher catch rates at the beginning of each season.
1039 Traditional vessels had higher catch rates which supports the hypothesis that their greater
1040 experience would result in stronger performance and make them effective indicators for
1041 less experienced fishers. Shippagan, Big Cove and Newport Point were the largest
1042 homeports, with at least 100 hundred vessels fishing, and had significantly higher catch
1043 rates than vessels from the other homeports. It suggests that maybe these homeports are
1044 the driving forces behind the minimal homeport clustering and may be sharing their
1045 information more.

1046 A possible limitation to the study of this fishery is the varying amounts of licenses
1047 given each year. The early 1990's did not have as many vessels fishing as in the 2000's
1048 which could impact the potential for communication occurring. This could be a factor in
1049 the random distributions of vessels based on type and homeport location observed for the
1050 early 1990's. Another reason for clustering of vessels from similar homeports could be
1051 vessels trying to limit their distance traveled by cutting down on fuel costs and settling
1052 for a similarly productive area that is closer to home resulting in lower fuel costs and
1053 weather constraints. A limitation in terms of communication, is that it is not possible to
1054 measure what type of communication is occurring in this fishery (verbal or observation)
1055 and its extent within the snow crab fishery. Future studies could be done by monitoring

1056 communication by radio or while at port. Palmer (1991) was able to monitor
1057 communication in the Maine lobster fishery, but that fishery is smaller with fewer
1058 homeports, so would require considerable research effort to monitor that much
1059 communication.

1060 The results support the possibility of communication occurring between vessels.
1061 The next step would be to analyse the impacts of clustering vessels on abundance, and
1062 catch rates at individual grids. This study supports the hypothesis of clustering amongst
1063 types, but is it clustering at certain grids in particular driving these results and are these
1064 grids close to certain homeports? The methods used in this chapter could be implemented
1065 in other fisheries that are not as well monitored and managed as the snow crab fishery. If
1066 possible, further research could be done into the actual communication occurring in the
1067 Gulf of St. Lawrence snow crab fishery by monitoring radio and dock communication
1068 and the impact at the grid scale that the clustering has on the snow crab population.

1069 The main goal of management in the context of the snow crab industry is to
1070 ensure the long-term sustainability of the fishery, and the collaboration between the two
1071 is more than most fisheries can accomplish. We manage the snow crab fishery by
1072 managing the fleet; how much they fish, how many licences are distributed and when the
1073 fishery opens and closes, not unlike many other commercial fisheries. The snow crab
1074 fishery is considered a well-managed fishery, but by filling in knowledge gaps,
1075 management can provide detailed strategies for the vessels (i.e. when to avoid clumping
1076 or overfishing a location). The snow crab fishery is an important part of Canada's
1077 economy and exploring these relationships amongst vessels may help management

1078 determine the amount of each type of license given each year, and help in setting the
1079 quotas to ensure the long-term biological and economic sustainability of the fishery.

1080

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1210 **Chapter 3 - Modelling Vessel Dynamics of the Gulf of St. Lawrence**
1211 **Snow Crab (*Chionoectes opilio*) Fishery Using Agent-Based**
1212 **Modelling**

1213 **Abstract**

1214 Agent-based modelling (ABM) was applied to the Gulf of St. Lawrence snow crab fishery to
1215 model vessel dynamics. The goal was to determine the impact of having public information vs.
1216 private information exchange. There are two types of vessels in the fishery, traditional (more
1217 experience) and non-traditional (less experience) which may result in differing levels of
1218 communication and associations. Spatial associations between vessels from the same homeport
1219 and based on vessel type were quantified. There was a general trend of clustering of vessels from
1220 the same homeport and types of vessels with random distributions and dispersal with increasing
1221 distances. Vessels who had public information (pre-season survey results) had more stable
1222 landings. This ABM has the potential to be expanded upon in the future, and be used as a
1223 management tool to assess the impacts of management protocols on fisher's success and effort
1224 allocation.

1225

1226 **Introduction**

1227 Individual-based models (IBMs) and agent-based models (ABMs) have been around
1228 since the 1960's (DeAngelis and Mooij 2005, Grimm et al. 2006, DeAngelis and Grimm 2014).
1229 They are becoming popular analytical tools in ecology and evolutionary biology (DeAngelis and
1230 Mooij 2005, Grimm et al. 2006). Janssen (2005) described the importance of ABMs in ecology,
1231 as they are useful in capturing the complexity of a system at the individual level. Each individual
1232 organism within an ecosystem grows, develops, and changes many times throughout its life.
1233 There are variations in life histories amongst individuals within the same population, which
1234 makes them individually unique. Even among age groups within a species, there are many
1235 variations between the individuals and the way they interact with their environment. ABMs are a
1236 bottom-up approach to solving ecological problems by simulating the dynamics of the system
1237 using the individuals, interactions among the individuals, and interactions between the
1238 individuals and the environment (Uchmański and Grimm 1996, An et al. 2005, Tang and
1239 Bennett 2010). ABMs presently have applications in ecology, computer science, engineering,
1240 cognitive science, and social sciences (Sanchirico and Wilen 1999, DeAngelis and Mooij 2005,
1241 Tang and Bennett 2010).

1242 ABMs simulate complex adaptive systems allowing for individual, and adaptive
1243 behaviours to emerge. A basic ABM is comprised of at least one population of agents, an
1244 environment, and the events (described by rules that agents go through to interact with the
1245 environment). Agents are simplified representations of individuals from a real population
1246 (Uchmański and Grimm 1996, DeAngelis and Mooij 2005, Grimm et al. 2006, Tang and
1247 Bennett 2010). Rules are applied to the agents and can be based on behaviour, types of
1248 interactions between individuals, feeding/foraging, and swimming, and models their impacts

1249 with the macro-environment (Janssen 2005, Tang and Bennett 2010). The decisions an individual
1250 makes are in response to these set situations.

1251 The second aspect of ABMs, is the environment, where information, energy, and agents
1252 interact, and can be one, two, or three dimensional (Tang and Bennett 2010). Environments can
1253 be set up using GIS, matrices, grids, geometric features, vectors, and rasters, making the
1254 application of ABMs highly variable, although applicable to many problems. This allows the
1255 user to bring in simulated or real-life data depending on the question. The agents interact with
1256 the environment and in the process alter it according to the events or rules.

1257 The events and rules in ABMs simulate real-world sampling events with no impact to the
1258 actual fishery, or the environment, making it a useful tool in biology and ecology where many
1259 species face population pressures. An event is created by a set of rules that are applied to the
1260 agent and how they interact with the environment. These events update the state of the agents
1261 and the environment in the model. The events follow a timeline progression, but what sets ABMs
1262 apart from many other modelling tools is their success at simulating populations composed of
1263 discrete autonomous agents representing individuals (single or groups). The events are followed
1264 in order of setup in the model, but the events are randomly applied to the individuals (Tang and
1265 Bennett 2010) through each time step, meaning that each simulation's outcome will be different
1266 than the previous one. The agents interact amongst each other and the environment, and ABMs
1267 can capture the variation among individuals that classical differential-equations and difference-
1268 equation models can miss (DeAngelis and Mooij 2005).

1269 In the past five decades, there has been an increase in the frequency of IBM and ABM
1270 use in ecology and biology (DeAngelis and Mooij 2005, Grimm et al. 2006) applying a variety of
1271 programming tools. ABMs have also been used in fisheries to model fishing effort in single-

1272 species, single-fleet, multi-zone models, as well as multi-species, single-fleet, multi-zone models
1273 (Soulié and Thébaud 2006), bioenergetics models (Breck 1993, Van Winkle et al. 1993, Martin
1274 et al. 2012), predator-prey interactions between different trophic levels and mortality rates in
1275 fisheries ecology (Rice et al. 1993, Rose and Cowan 1993, Hovel and Regan 2008), fisheries
1276 quotas (Little et al. 2009), management strategies (Gao and Hailu 2012), travel behaviour
1277 (Anwar et al. 2007, Foss and Couclelis 2009), and population-environment research (Miller et al.
1278 2010). ABMs have also previously been used to model communication and information
1279 exchange outside of fisheries (Bernstein et al. 1991, Deadman 1999, Berger 2001, Little and
1280 McDonald 2007, Sakellariou et al. 2008) and even within fisheries (Dorn 2001).

1281 Another area of ABMs that has been expanding recently, is using an empirical approach
1282 to ABM. Janssen and Ostrom (2006) described using four different types of empirical methods,
1283 1) case studies, 2) stylized facts, 3) role-playing games and 4) lab experiments. They suggested
1284 that using an empirical-based method, or even combining methods could strengthen the results
1285 by looking at real world biological problems instead of answering a theoretical question. Using
1286 the data supplied by DFO (E. Wade, Gulf Fisheries Centre DFO, Moncton, Canada, personal
1287 communication, 2016) will allow this chapter to examine possible explanations for the
1288 associations observed in chapter two of this thesis.

1289 Recently in fisheries management there has been an increased need and interest to model
1290 fleet behaviour (Hilborn 1985, Branch et al. 2006) in response to regulation protocols and
1291 different management strategies. This allows management to predict outcomes of protocols and
1292 avoid real-life season closures or even complete fishery closures. ABMs allow for behaviours to
1293 evolve and adapt to changing environments over time without real-life consequences. This could
1294 model potential impacts of fishing bans on the economy and ecology of the fishery. There are

1295 only a few ABMs applied to fisheries, which mainly look at behaviours in response to
1296 regulations (Foss and Couclelis 2009, Little et al. 2009, Gao and Hailu 2012), or different forms
1297 of communication and impacts on catch per unit effort (CPUE) or catch rates (Dupont 2000). A
1298 study done by Soulié and Thébaud (2006) using the Cormas (Cormas 2014) modelling platform
1299 examined how a fleet targeting multiple species responded to changing regulations in a fishery
1300 by examining the steady-state equilibrium. Results showed that fishing bans impacted short-term
1301 profits but CPUE may remain profitable for high-effort fleets. When an area in the model had
1302 high biomass it had high CPUE, which then lead to a large reduction in biomass and a
1303 subsequent decline in CPUE. This large reduction in biomass could be occurring in the snow
1304 crab fishery if multiple vessels are communicating and fishing the same area. Other studies have
1305 also examined fleet behaviour in response to differing spatio-temporal scales (Dorn 2001) and
1306 individual transferable quotas (Little et al. 2009). Common elements used across these different
1307 studies in the fleets decision process were travel time, how close the next fishing patch is, size of
1308 fishing patch, when to participate in a fishery, how to select a patch, depth and time to fish, and
1309 what the vessel expected to catch (Dorn 2001, Little et al. 2004, Little et al. 2009). This chapter
1310 aims to apply similar methodology from Dorn (2001), Little et al. (2004), Soulié and Thébaud
1311 (2006) and Little et al. (2009) and examine how vessels are using the space over time, impacts of
1312 information exchange on spatial associations and how total yearly landings are impacted.

1313 There has been previous work done using ABMs in fisheries ecology examining
1314 predator-prey interactions, or information exchange, but to my knowledge never combining the
1315 two together to examine resulting spatial associations due to communication or information
1316 exchange within a fishery. An ABM approach was chosen to examine the relative impact of
1317 public information (pre-season survey data given to all vessels) and the private information

1318 (personal experience) exchange on effort aggregation and fishing success. I also wanted to
1319 examine the impacts of varying levels of communication on spatial associations. The ABM aims
1320 to examine the spatial associations of vessels with public information (the pre-season survey
1321 trials) and without (naïve trials) and then examining private communication (based on homeport
1322 location or vessel type) and impacts on catch rates and effort aggregation for every vessel. I will
1323 use my model to test whether simple information sharing can generate aggregation patterns
1324 similar to those observed in the actual fishery and impact the fleets overall success (total yearly
1325 landings of the entire fleet) and whether having prior knowledge of the upcoming season impacts
1326 success (see Chapter Two).

1327 **Materials and Methods**

1328 **Agent-based modelling using NetLogo**

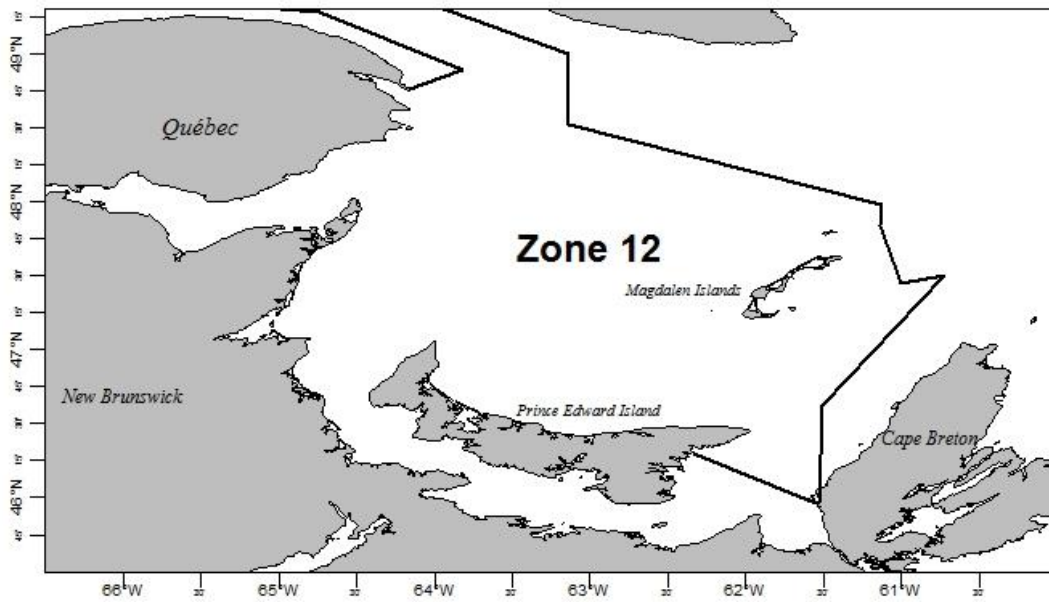
1329 There are many different modelling languages available for agent-based modelling such
1330 as AgentScript (Densmore 2013), MATLAB (Mathworks 2018), Cormas (Cormas 2014),
1331 NetLogo (Wilensky 1999), and GAMA (Grignard et al. 2013) to name a few, with CoMSES
1332 (CoMSES Net 2018) having a database of other programs. NetLogo (Wilensky 1999) is
1333 becoming one of the most popular in terms of use in ecology (Van Winkle et al. 1993,
1334 Uchmański and Grimm 1996, Grimm et al. 2006, Railsback and Grimm 2011, Wilensky and
1335 Rand 2015), social sciences (Gilbert and Troitzsch 2005), economics (Tesfatsion 2002),
1336 geography (Parker et al. 2002, An et al. 2005), and political sciences (Lempert 2002). NetLogo
1337 is a free, open-source software that includes a coding dictionary, interactive interface, and code
1338 libraries, and for these reasons was chosen as the modelling tool for this study. In the subsequent
1339 descriptions, NetLogo variables will be indicated in bold-faced type.

1340 **The Fishery**

1341 *The environment*

1342 In the Gulf of St. Lawrence (GSL) snow crab fishery, after the season has finished,
1343 Fisheries and Oceans Canada (DFO) conducts their yearly survey. The survey provides vessels
1344 with information on available male snow crab for the next year in zone 12 (Figure 3.1). The data
1345 collected from these yearly surveys were provided by DFO (E. Wade, Gulf Fisheries Centre
1346 DFO, Moncton, Canada, personal communication, 2017) to create annual abundance files. DFO
1347 created 10x10 minute patches of the fishery to represent the different fishing areas. Crab
1348 abundance was estimated for each of the 234 fishable patches from the yearly survey data using
1349 kriging with external drift (a geostatistical technique) (Webster and Oliver 2001) using depth as a
1350 secondary variable (Wade et al. 2014). Kriging is done to estimate a random variable at one or
1351 more unsampled areas. The drift represents a mean that is not stationary. The information for
1352 each fishing patch in the fishery was then used to create an abundance patch map in NetLogo. A
1353 total of 25 years of biomass data was supplied, ranging from 1990-2015 (excluding 1996) (Table
1354 3.1).

1355 In the NetLogo language, the snow crab abundance was used to setup patches that define
1356 the environment. The patches are the squares (Figure 3.2) that approximate 10x10 minute
1357 regions covering the Gulf as described by DFO, and a 19x33 square world was setup in Netlogo.
1358 Each patch contained information on the current, start, and end of season snow crab abundance,
1359 effort, patch identification name and number, if that patch is water or land and if it is fishable or
1360 not, quality of the patch compared to the other patches, detours (route to follow) to avoid vessels
1361 running aground, the cumulative effort expended in the patch and the catch taken from it. For
1362 visual representation of the fishery each patch was set to an orange shade to indicate snow crab



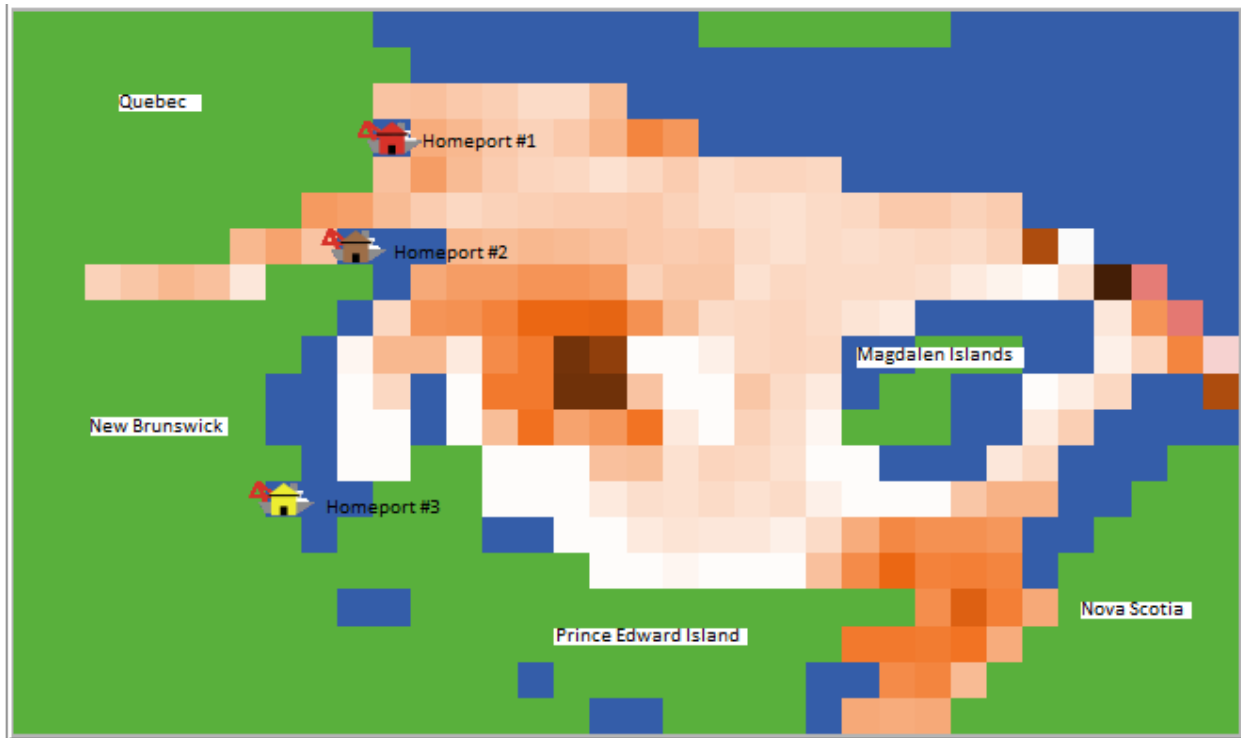
1363 **Figure 3.1** A map of the Gulf of St. Lawrence snow crab fishery. Zone 12 is the focus for
1364 **the thesis** as it is the largest in terms of size and number of vessels fishing each season.
1365 **Vessels** originate from four provinces: New Brunswick, Quebec, PEI, and Nova Scotia.

1366

1367 **Table 3.1 A conversion table for what year each NetLogo year represents in the snow crab**
1368 **fishery in the Gulf of St. Lawrence. 1996 is the only year missing.**

Fishing season	NetLogo Year
1990	1
1991	2
1992	3
1993	4
1994	5
1995	6
1997	7
1998	8
1999	9
2000	10
2001	11
2002	12
2003	13
2004	14
2005	15
2006	16
2007	17
2008	18
2009	19
2010	20
2011	21
2012	22
2013	23
2014	24
2015	25

1369



1370 **Figure 3.2 A map of zone 12 in the Gulf of St. Lawrence snow crab fishery in NetLogo.**
 1371 **Green represents land, blue is water outside the zone and the orange-white range of colours**
 1372 **are based on snow crab abundance in each patch and are the fishable patches. The three**
 1373 **homeports with their vessels are represented here as well.**

1374

1375 abundance (density) if it was fishable, blue for non-fishable water, and green for land (Figure
1376 3.2). Since the Magdalen Islands are in the middle of the water, there were many vessels that
1377 were unable to navigate around the island without setting up the detours previously mentioned.
1378 Therefore, any water patch that was beside a land patch was assigned a **detour-east** value from
1379 0-360 degrees and similar for **detour-west** depending on the direction (boat facing left or right in
1380 the interface simulation) the vessel was moving (east & right for going to fish and west & left for
1381 going back to homeport).

1382 *The agents*

1383 In this model there were three types of agents (patches, homeports and the fleet), but for
1384 this section we will examine the homeports and the fleet as the main agents and consider the
1385 patches as part of the environment for simplicity. There were three homeports from where the
1386 fleet could originate. Three homeports were chosen based on results from the focus dataset in
1387 Chapter 2. Since there were 9 homeports that were located in three distinct areas, three
1388 homeports were chosen to represent the group of homeports from Québec, northern New
1389 Brunswick, and southern New Brunswick.

1390 Each vessel agent had a variable representing its fuel, homeport ID, location, how much
1391 they have caught on their trip, their vessel type's catchability, how much a vessel can hold and
1392 what is presently being held, the speed they are travelling, which patch they are targeting at the
1393 moment, how much they have caught during the season, how much they have earned from this
1394 catch, the fuel expended for each trip, the effort expended during the trip, the direction they are
1395 travelling, their experience, how much they expect to catch and when the trip started.

1396 A starting amount of **fuel** was given to a vessel when they were at their respective
1397 homeports and was depleted throughout a trip. Fuel cost was set at two in the interface to

1398 incorporate fuel as a decision factor in choosing a patch. This value would require vessels to
1399 consider how far they traveled to fish by updating the values allocated to each location by the
1400 cost of travel in the experience matrices but wouldn't be highly limiting to travel further if the
1401 patch was highly desirable.

1402 The **kind** was either traditional or non-traditional with different **q** values (catchability
1403 coefficient of how efficient a vessel is at catching fish). The **q** for traditional was set at 0.005,
1404 and the **q** of non-traditionals at 0.0025, for the models to represent the differences between the
1405 vessels, experience, gear, and catch differences observed in the fishery.

1406 Each vessel was allowed a **hold-capacity** of 10,000 which was chosen by examining the
1407 distribution of each vessels highest catch rate from the full dataset from chapter two (75% of the
1408 vessels were just below 10,000 kg of fish), so **hold-capacity** was set for each vessel at 10,000 in
1409 the model and the **hold** and **total-year-catch** was updated as vessels caught fish. A **bank**
1410 variable represented the total past landings of a vessel. The **direction** was assigned based on
1411 vessels activity, if they were going out to fish they were assigned east, and west if they were
1412 heading back to port.

1413 Vessels were given initial knowledge matrices to start their season. This allowed the
1414 vessel to come into the fishery with a certain amount of knowledge (pre-season survey data
1415 known as survey in this chapter) or no knowledge at all (naïve). This matrix was known as initial
1416 value matrix, which assigned a value to each fishable patch. The equations for setting up these
1417 matrices will follow in the rules/events section. These matrices represent all of the patches in the
1418 NetLogo world and determine where a vessel will go fish next depending on the value assigned
1419 to the patches. These values begin at zero (no desire to fish in this area) and increase with
1420 increasing desirability (based on what they expect to catch, abundance of snow crab, fuel cost

1421 and distance to travel). The initial matrix of each vessel is updated as the vessels fish and gain
1422 experience, defining the “desirability” of each patch.

1423 *The rules/events*

1424 Two different trials were set up to examine the effects of pre-season survey knowledge
1425 compared to naïve fishing. In the trials there was an initial knowledge matrix that helps a vessel
1426 choose which patch will be targeted but differs from naïve to pre-season survey trials. In the
1427 trials where the vessels were naïve, their initial knowledge matrix was set up with every single
1428 fishable patch being given a value of one. This represented the vessels having zero knowledge of
1429 the fishery and each patch is considered equally productive in terms of how many snow crabs
1430 there are to catch. In the survey trials, the initial beginning of season matrix was setup such that
1431 each fishable patch was assigned an initial value through the following equation in NetLogo
1432 format:

$$1433 \quad 3.1 \quad \mathbf{init-value} = (\mathbf{start-sc} * \mathbf{q-trad}) - (\mathbf{dist-to-shippigan} * \mathbf{fuel-cost})$$

1434 where **init-value** is the initial value assigned to a patch at the beginning of the season, **start-sc**
1435 was the total amount of snow crab in the patch in question at the start of the season, **q-trad** was
1436 the value of what traditionals were expected to catch per time step, **dist-to-shippigan** was the
1437 distance to the “main” homeport or the one in the middle of the other two for simplicity, and
1438 **fuel-cost** is the value described previously to represent the cost of fuel. No fishable patch could
1439 be assigned a value of less than one. This equation was created to incorporate different aspects of
1440 what would make a fishing patch be chosen, how many snow crabs are in it, is it a good fishing
1441 location, how far from homeport is it, and the cost associated with travelling there. As experience
1442 is gained from fishing in patches, this beginning initial matrix is then updated into an experience
1443 matrix and is applicable in both the naïve and survey trials using the following equation:

1444 3.2 **experience-mod** = (**catch** - ((**distance** **home-grid**) * **fuel-cost**))

1445 where **experience-mod** represents the updated matrix of experience gained during the fishery,
1446 **catch** represents how much was actually caught in the area, **distance** is a function in NetLogo
1447 that calculates the distance of where the agent is to the value proceeding the distance variable,
1448 **home-grid** is the patch containing the homeport that vessel originates from, and **fuel-cost** as
1449 previously described. This again takes into account if that trip was successful (based on how
1450 much they caught), and the cost of travel. The experience of that patch is then averaged with the
1451 old experience and updated in the vessel's fishing experience matrix. These values assigned to
1452 the patches in the matrices are what is shared during the communication trials to whichever
1453 vessels are included.

1454 The scale of distances is different between Chapter 2 and 3 since the smallest scale we
1455 can obtain in NetLogo is each individual patch's midpoint coordinates, while the fishery data
1456 have exact locations within a patch. Furthermore, the true grid's vary in bathymetry and crab
1457 density while the model patches are uniform. Coordinates for whole patch midpoints were
1458 transformed into Universal Transverse Mercator (UTM) coordinates for spatial analysis.

1459 A fishing season lasts a maximum of 90 days (2160 hours). Each fishing season was split
1460 into three sections (0-720 hours was the beginning of the season, 721-1440 was the middle of the
1461 season, and 1441-2160 for the end of the season). Analysis focused on the mid-season where
1462 experience can modify information but local depletion is limited. The middle portion of the data
1463 were subset, keeping only the trips between 721 and 1057 hours to represent the first two week
1464 period of the middle fortnight of year (FOY) for consistency as done in chapter two. This FOY
1465 data was then used in the Mantel test and Ripley's K section of analysis.

1466 In the actual fishery there was generally a 3:1 ratio of traditional vessels to non-
1467 traditional vessels, so for consistency in the ABM models, 45 traditional and 15 non-traditional
1468 were created at each homeport. This gave a total of 135 traditional vessels and 45 non-
1469 traditionals.

1470 The parameter **interference** was also included in the model. Interference is the negative
1471 impact of local density (number of other vessels) on fishing efficiency with 1 being very strong
1472 (1/total number of vessels) and 0 being no interference (Gillis and Peterman 1998). It was
1473 represented by the following equation in NetLogo format:

$$1474 \quad 3.3 \quad \text{catch} = \text{biomass} * \mathbf{q} * \mathbf{nVessels} ^ (- \mathbf{interference})$$

1475 where **catch** represents how much a vessel caught in that patch, **biomass** is the total abundance
1476 of snow crab at that exact time, **q** is the catchability set to each individual type of vessel
1477 (traditional or non-traditional), **nVessels** is the number of other vessels fishing in that patch, and
1478 **interference** as previously described was set at 0.5.

1479 *Trials*

1480 To examine the impacts of having prior knowledge of the fishery, two sets of trials were
1481 run: survey and naïve. Survey represented the pre-season survey data (public information) given
1482 to all the vessels fishing. The naïve trial represented vessels starting with zero knowledge of the
1483 fishery. Within those naïve and survey trials, three main trials were setup with two subsets within
1484 them for a total of 5 distinct trials. The three main trials were 1) no communication at all, 2)
1485 homeport communication, 3) and everyone communicating. The subsets of these trials were 1)
1486 Traditionals and non-traditionals are both included in the type of communication (ON in the
1487 model and results) 2) only the traditional vessels are included in the communication (off in the
1488 model and results).

1489 In order to examine varying levels of communication, a variable was created, **others-**
1490 **weight**, to represent how much a vessel takes into account the other vessel's crew's fishing
1491 experience. The **others-weight** was valued from 0.1-1, with 0.1 representing almost zero belief
1492 and one being complete belief of the other vessel's crew's experience and incorporating it into
1493 their own experience matrix. Three values of others-weight were considered (0.1, 0.5 and 1)
1494 making up the total of 15 trials. To examine how vessels were using the pre-season survey data,
1495 another 15 trials following the same protocol were set up for vessels except they started off with
1496 zero information about the fishery (naïve trials). A total of 30 trials were completed across 25
1497 years of historical abundance data.

1498 To compare whether levels of associations varied across years of higher landings vs.
1499 years of lower landings, two extreme years (14 and 19 respectively) were examined following
1500 similar steps as described above, although each year was replicated 30 times. These 30 replicates
1501 were combined for confidence in comparing the two years (14 representing a year of higher
1502 landings and 19 with lower landings). Total effort was examined across all the lower and higher
1503 landing years and 14 and 19 had similar total effort per year and represented two different
1504 landing years, and were therefore chosen to represent the two extremes for maximum contrast.

1505 *Section 3.1- Vessel associations based on homeport location*

1506 To test whether vessels from the same homeport were fishing in similar areas, a Mantel
1507 test was performed (Mantel 1967). Mantel tests look for spatial correlation between two
1508 matrices, as described in Chapter 2. Similar to Chapter 2, a fishing matrix and a homeport matrix
1509 were set up by calculating the distances between each vessel's homeport and the distances
1510 between their fishing locations. The homeport matrix was set up so that the homeport locations
1511 of each ordered vessel were in the rows and columns and the distances between them made up

1512 the matrix. The fishing location matrix was set up in the same way but using the fishing
1513 coordinates. They were then analysed using the ade4 (Dray and Dufour 2007) package in R (R
1514 Core Team 2015) and a correlogram was created in the vegan package (Oksanen et al. 2017).
1515 Similar to Chapter 2, the Mantel tests were based on 1000 permutations ($\alpha = 0.05$) using a
1516 Pearson correlation (Legendre and Fortin 2010). Since the spatial scales are not as precise as the
1517 real fishery data, four different distances were analysed in the Mantel tests (30, 90, 150, and 210
1518 km).

1519 *Section 3.2- Associations based on vessel type*

1520 In the NetLogo model, vessel type as described in Chapter 2, was known as **kind** because
1521 type is a function in the NetLogo language. To test whether vessel type had an impact on where
1522 vessels fished, Ripley's K function was used to test for evidence of different spatial patterns
1523 (Cox and Lewis 1972, Van Lieshout and Baddeley 1999). Similar to Chapter 2, the different
1524 types of associations between and within vessel types were examined using the K_{cross} and K_{est}
1525 functions respectively in the spatstat package (Dixon 2002) in R (R Core team 2015) across the
1526 six distances chosen (15, 30, 60, 75, 90, 100 km). To test the model at a significance level of
1527 $\alpha=0.05$, and 1000 simulations (Baddeley and Turner 2005, Dixon 1994, Dixon 2012) were done
1528 using a confidence envelope around the H_0 (null) of complete spatial randomness (CSR).

1529 For graphical comparisons of K values, the distance between the confidence interval
1530 envelope of randomness and the estimated K value were examined across the different types of
1531 communication for every year. In this standardization, K values that fall within the null envelope
1532 will have a distance of zero.

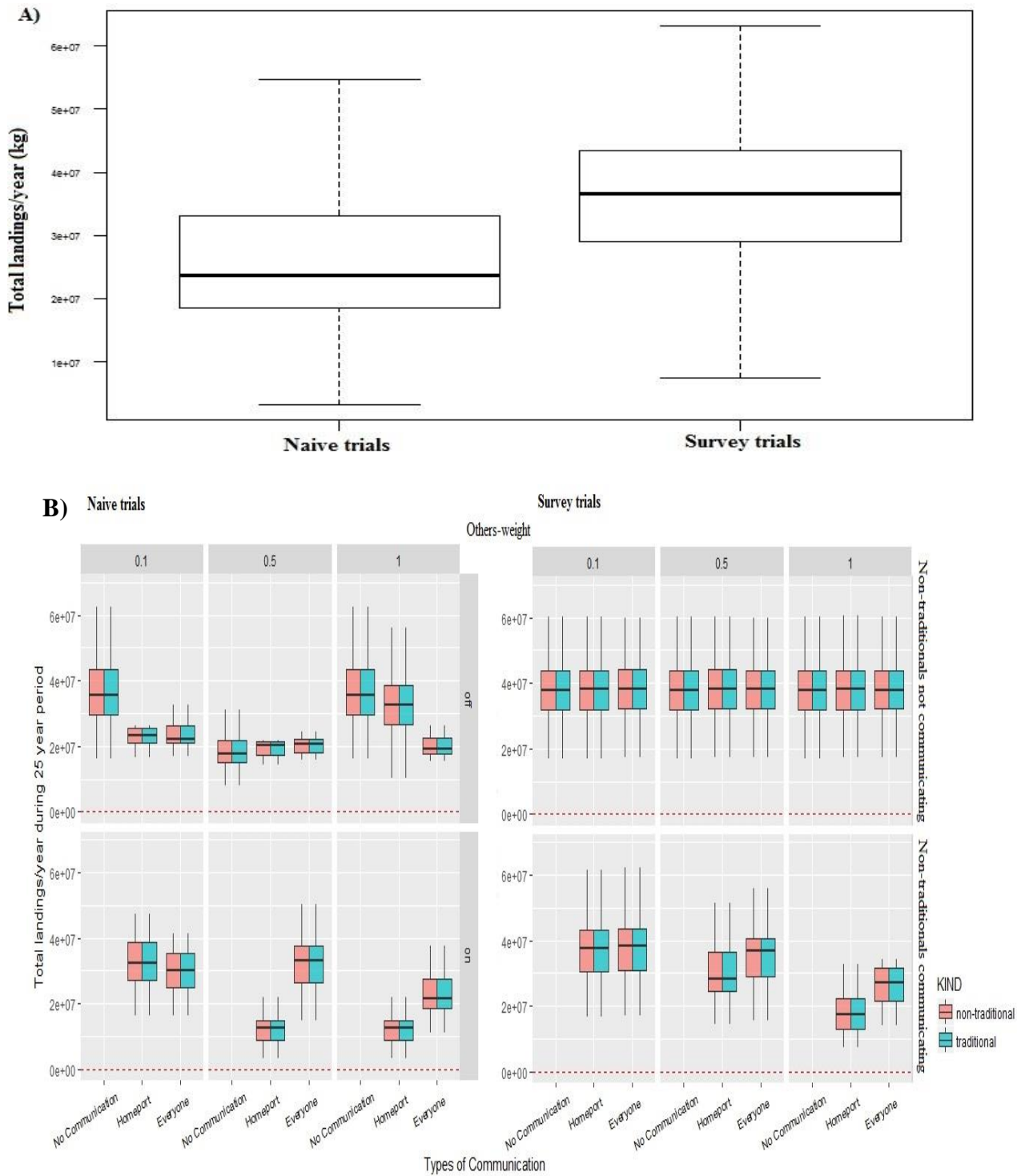
1533 **Results**

1534 Examining the differences in total landings per year between the naïve and survey trials
1535 showed that there were higher landings during the survey trials (Figure 3.3 A). There were
1536 differences in landings across the different types of communication (Figure 3.3 B). In the naïve
1537 trials there were higher landings when there was no communication. In the survey trials the total
1538 landings were the same across the different others-weights and communication trials. Lower
1539 landings were generally observed when everyone communicated. The total landings per year
1540 followed similar trends to peaks and troughs of snow crab abundance and generally total yearly
1541 landings followed trends in abundance (Figure 3.4) with minor differences per year in the
1542 different communication trials. Years of higher landings (year 14) had similar results while there
1543 were fewer differences between trials of lower landings (year 19) (Figure 3.5).

1544 In the survey trials there were higher landings when everyone was communicating,
1545 vessels from the same homeport and during no communication with exceptions being observed
1546 when the non-trationals were included in the communication. Total yearly landings were lower
1547 in these trials when non-traditional vessels were communicating, and higher when they were not
1548 (Figure 3.3 B). Years 14 had similar results with while there were fewer differences between
1549 trials in year 19 (Figure 3.5)

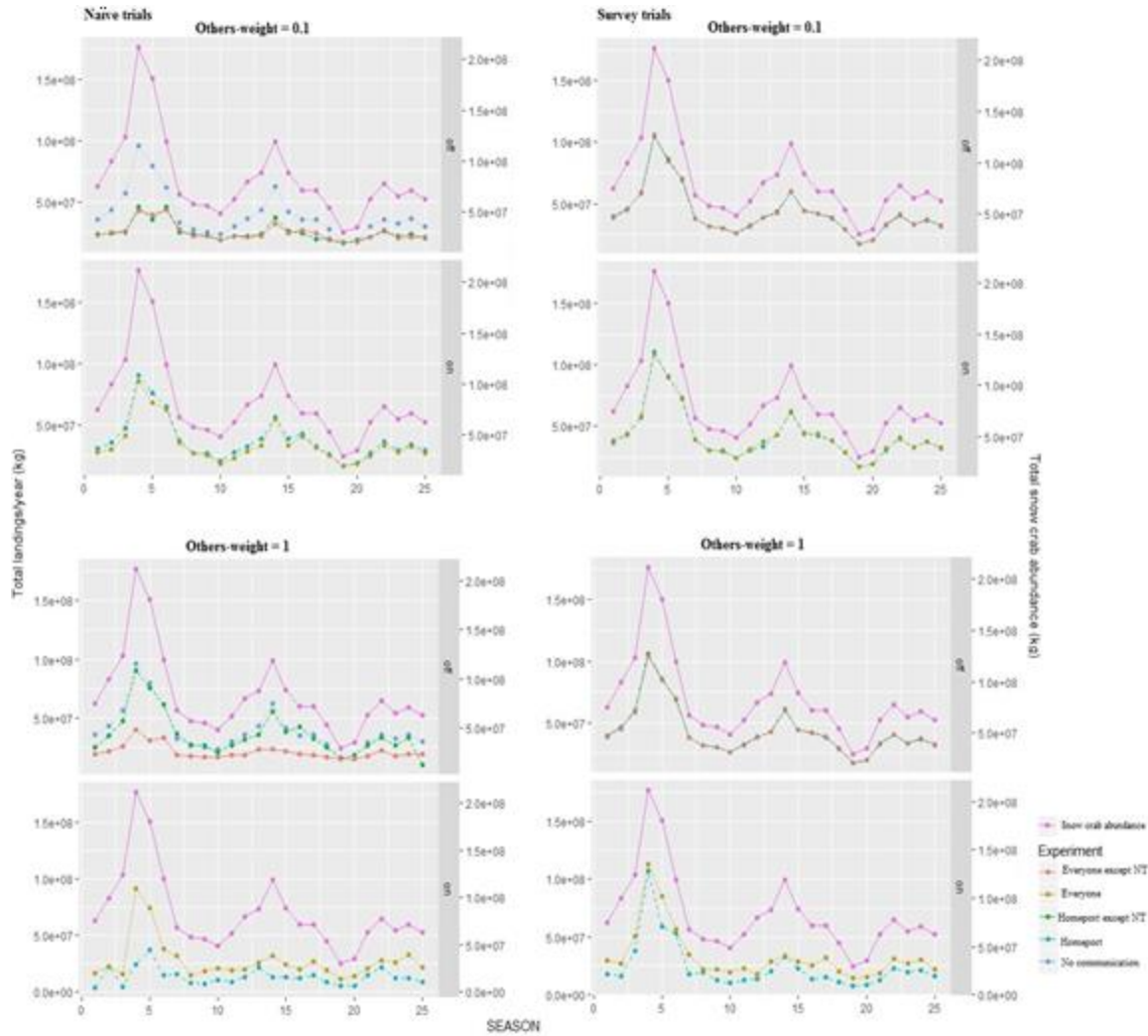
1550 *Section 3.1- Vessel associations based on homeport location*

1551 Vessel associations based on homeport location were plotted on a correlogram across the
1552 30 different trials, and can be observed in a representative correlogram (Figure 3.6) from the
1553 homeport trial at others-weight of 1. Instead of examining 30 different correlograms, the results
1554 were combined to create Figure 3.7. Across the naïve and survey trials vessels from the same
1555 homeport were clustering at the 30 km range, and as distance increased, associations were



1556 **Figure 3.3 A)** The total landings of every trial each with 25 years of results, were combined
 1557 **to compare the total landings for the entire fishery between the naïve and survey trials. B)**
 1558 **A more in depth look at the unique trials to examine possible trends in the total landings**
 1559 **across the survey and naïve trials for each others-weight, communication experiment, and**
 1560 **whether the non-traditionals were communicating or not.**

1561

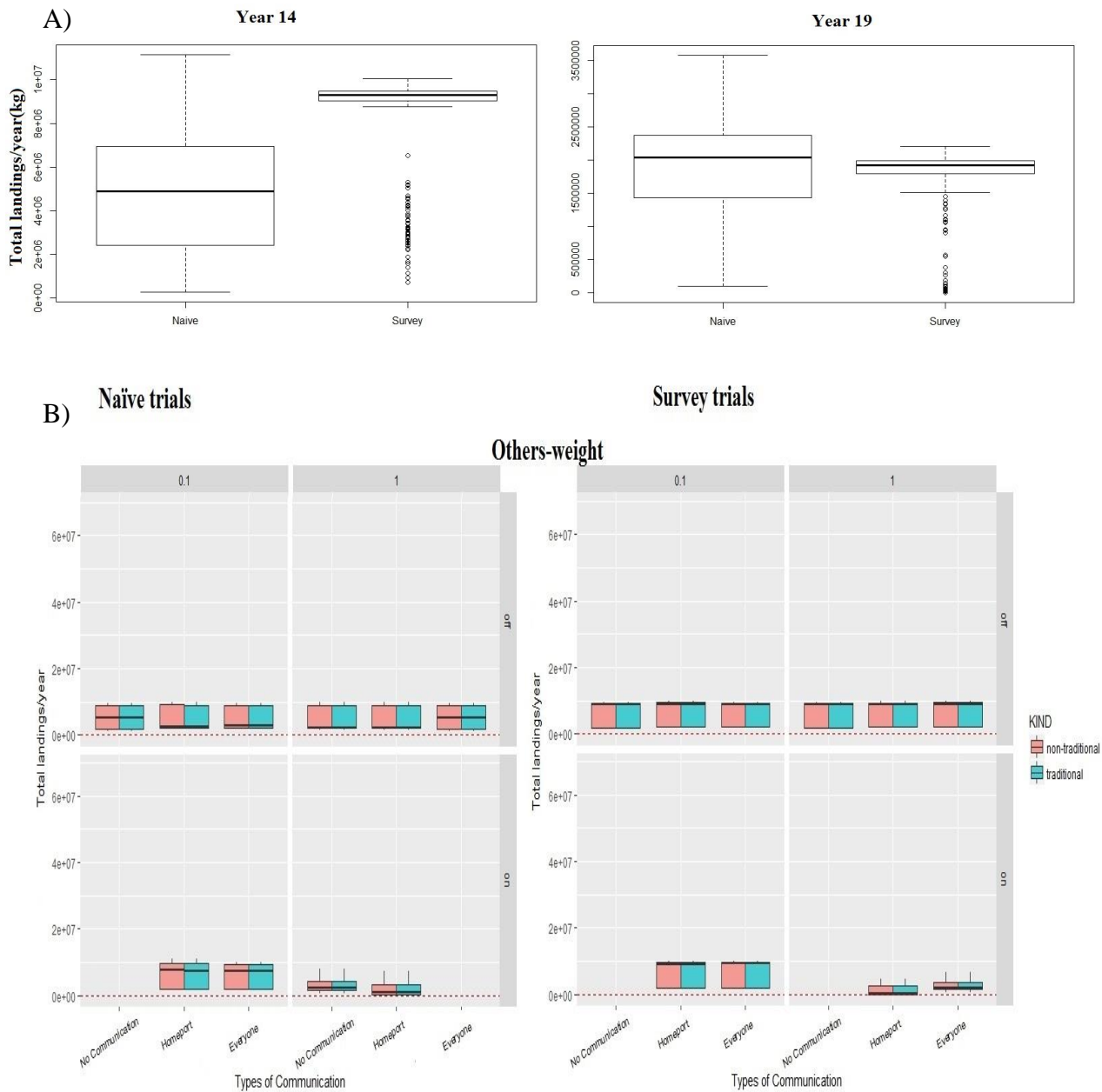


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1577 **Figure 3.4** Graphically representing snow crab abundance and the total landings for the
 1578 **whole fishery** each season at the different weights for others-weight and experiments.
 1579 **Everyone except NT** represents the non-traditional vessels not being included but every
 1580 **traditional vessel is communicating**. **Everyone** is every vessel from every homeport is
 1581 **communicating**. **Homeport except NT** represents just the traditionals from the same
 1582 **homeport communicating**. **Homeport** represents every vessel from the same homeport is
 1583 **communicating**. **No communication** represents trials where no vessel is communicating. **On**
 1584 **and Off** represent non-traditionals included in communication (on) and non-traditionals
 1585 **not included in communication (off)**. **Others-weight of 0.5 was dropped to just look at the**
 1586 **extreme values for others-weight.**

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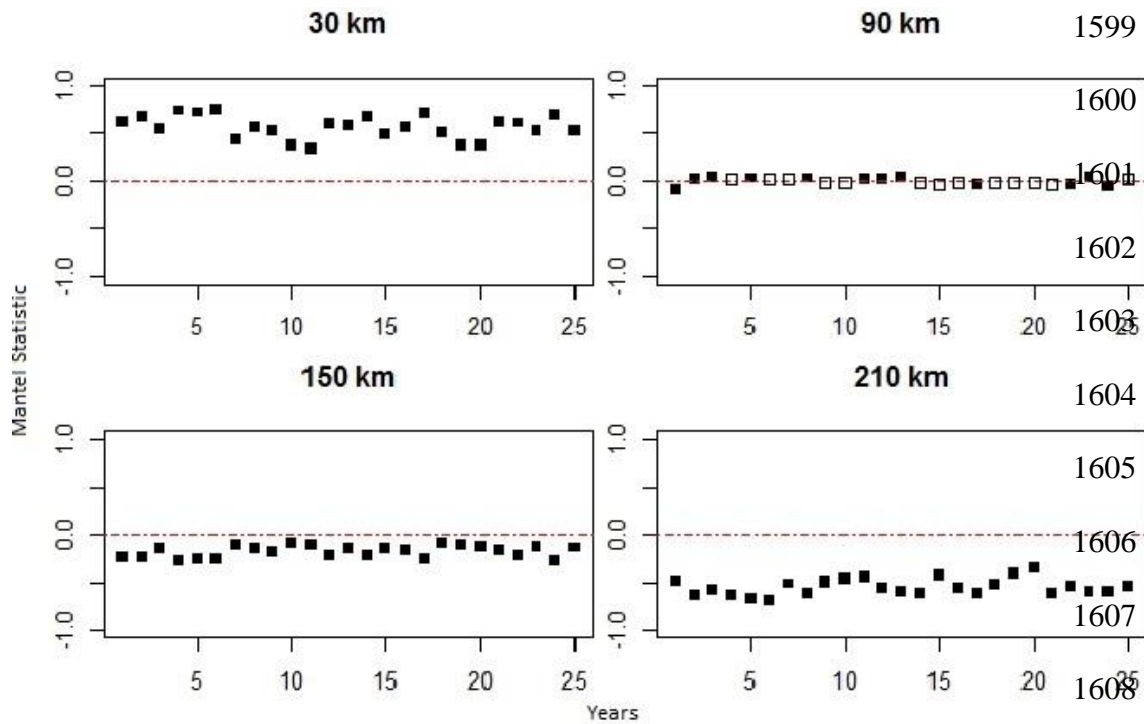
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1590 **Figure 3.5 A) The total landings of every trial each with 30 replications of results, were**
 1591 **combined to compare the total landings for the entire fishery between the naïve and survey**
 1592 **trials for high and low landing years (years 14 and 19 respectively). B) A more in depth**
 1593 **look at the unique trials to examine possible trends in the total landings across the survey**
 1594 **and naïve trials for each others-weight, communication experiment, and whether the non-**
 1595 **traditional were communicating or not with the 30 replicates combined.**

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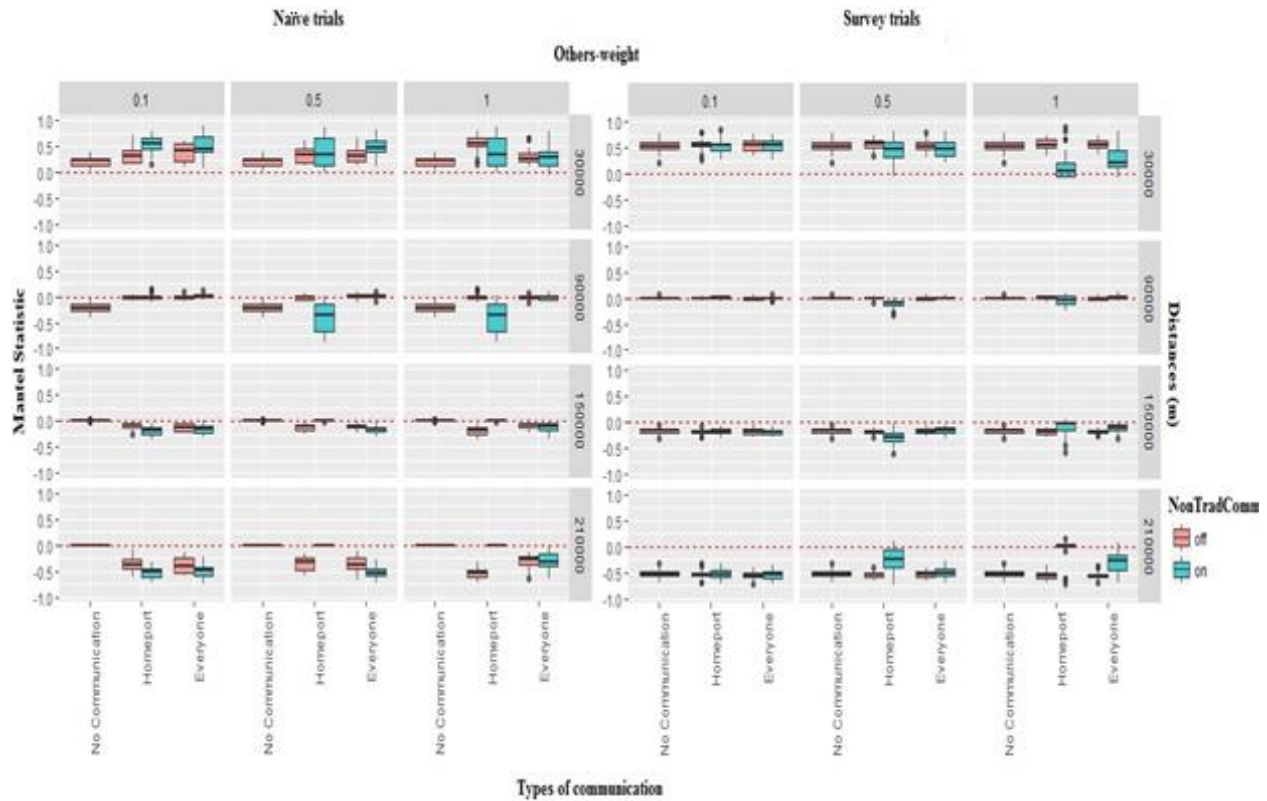
1609 **Figure 3.6 Using a correlogram to plot the results from the Mantel test looking at four**
 1610 **distances (30, 90, 150 and 210 km) across all 25 years for homeport communication trial**
 1611 **and others-weight of 1. A negative value indicates dispersion and a positive is clustering of**
 1612 **vessels. Zero represents a random distribution. Testing alpha=0.05. Black squares**
 1613 **represent significant values while the white ones are non-significant. The dashed line**
 1614 **represents the Ho: of a random distribution. Each type of communication for each weight**
 1615 **was tested for non-traditionals communicating or not for the naïve and survey trials. To**
 1616 **avoid plotting all 30 correlograms the results were combined to create Figure 3.7.**

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1621 **Figure 3.7** The results for Mantel tests across the different distances, communication type
 1622 **trials, weights and whether the non-traditionals were included in the communication (on)**
 1623 **or not (off) for the naïve and survey trials. Each Mantel test is based on the whole fleet**
 1624 **regardless of the type of communication occurring and each box plot is each of the 25 years**
 1625 **of data combined based on the snow crab pre-season distributions. On and Off represent**
 1626 **non-traditionals included in communication (on) and non-traditionals not included in**
 1627 **communication (off).**

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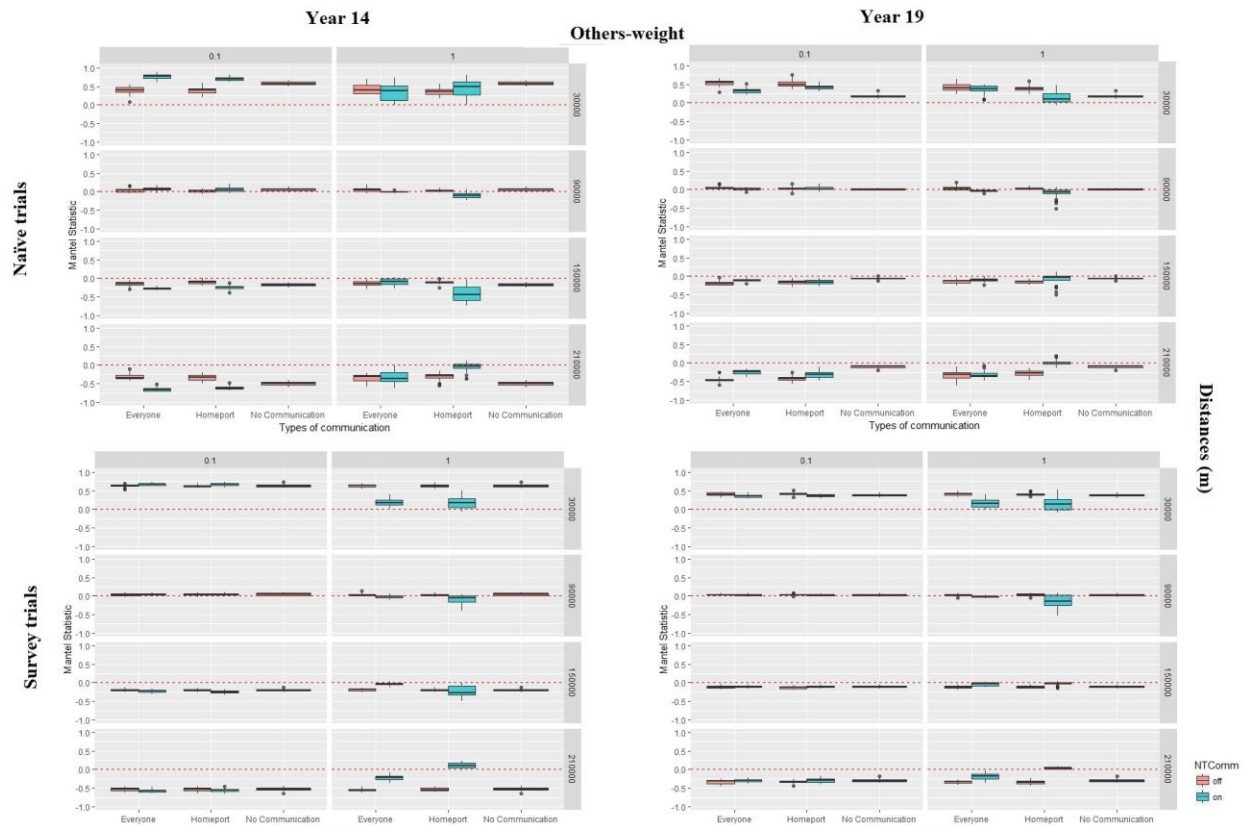
1636 random and then dispersed at the highest distances (Figure 3.7). This pattern was not only
1637 observed across the naïve and survey trials, but also across the three others-weight values (0.1,
1638 0.5 and 1). The only difference was seen at others-weight = 1 and 30 km where there were
1639 significant differences between the results of when vessels from the same homeport and trials
1640 where everyone was communicating where associations were significantly different from the
1641 other trials results. When non-traditional vessels were not included in the trials, there were lower
1642 levels of clustering (at 30 km) and lower levels of dispersal (210 km). When non-traditional
1643 vessels were communicating, associations tended to be closer to random across every distance
1644 and type of communication. Clustering was the highest when the non-traditionals were not
1645 included in the communication trials (Figure 3.7).

1646 Years 14 and 19 were examined to represent high and low abundance years to test for
1647 differences in associations. Results were similar to those described above (Figure 3.8). The only
1648 difference was at others-weight = 0.1 the associations were slightly higher in the homeport
1649 communication trials when non-traditional vessels were included in the communication.

1650 *Section 3.2- Associations based on vessel type (kind)*

1651 Trends in spatial associations based on vessel type were similar to the homeport
1652 associations. A typical result plot for Ripley's K estimates was plotted in Figure 3.9 from the
1653 communication trial at others-weight = 1. A total of 30 plots were created, and similar to the
1654 Mantel results, were combined and a standardized distance was calculated to create Figures 3.10
1655 and 3.11. At the smaller spatial scales (15 and 30 km) there was clustering of vessels and as
1656 distance increased associations were random (Figure 3.10).

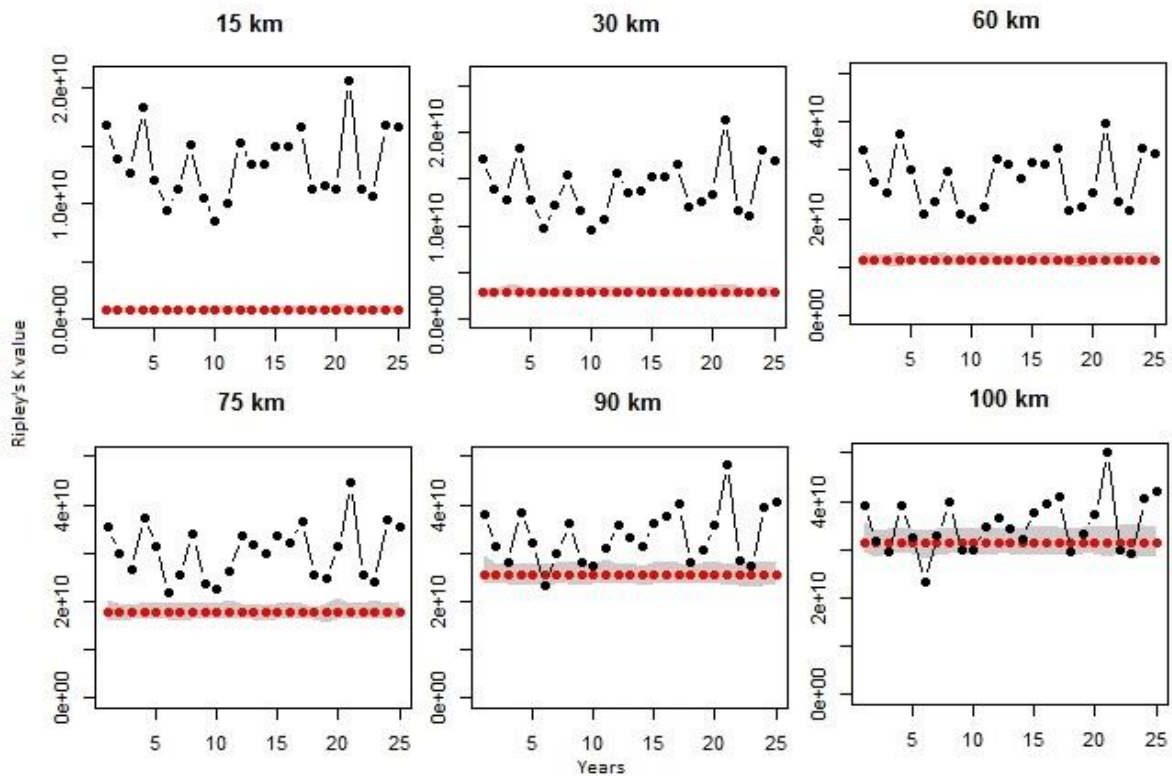
1657



1658 **Figure 3.8** The results for Mantel tests across the different distances, communication type
 1659 **trials, weights and whether the non-traditionals were included in the communication (on)**
 1660 **or not (off) for the naïve and survey trials for years 14 and 19. Each Mantel test is based on**
 1661 **the whole fleet regardless of the type of communication occurring and each box plot is each**
 1662 **of the 30 replications combined based on the snow crab pre-season distributions. On and**
 1663 **Off represent non-traditionals included in communication (on) and non-traditionals not**
 1664 **included in communication (off).**

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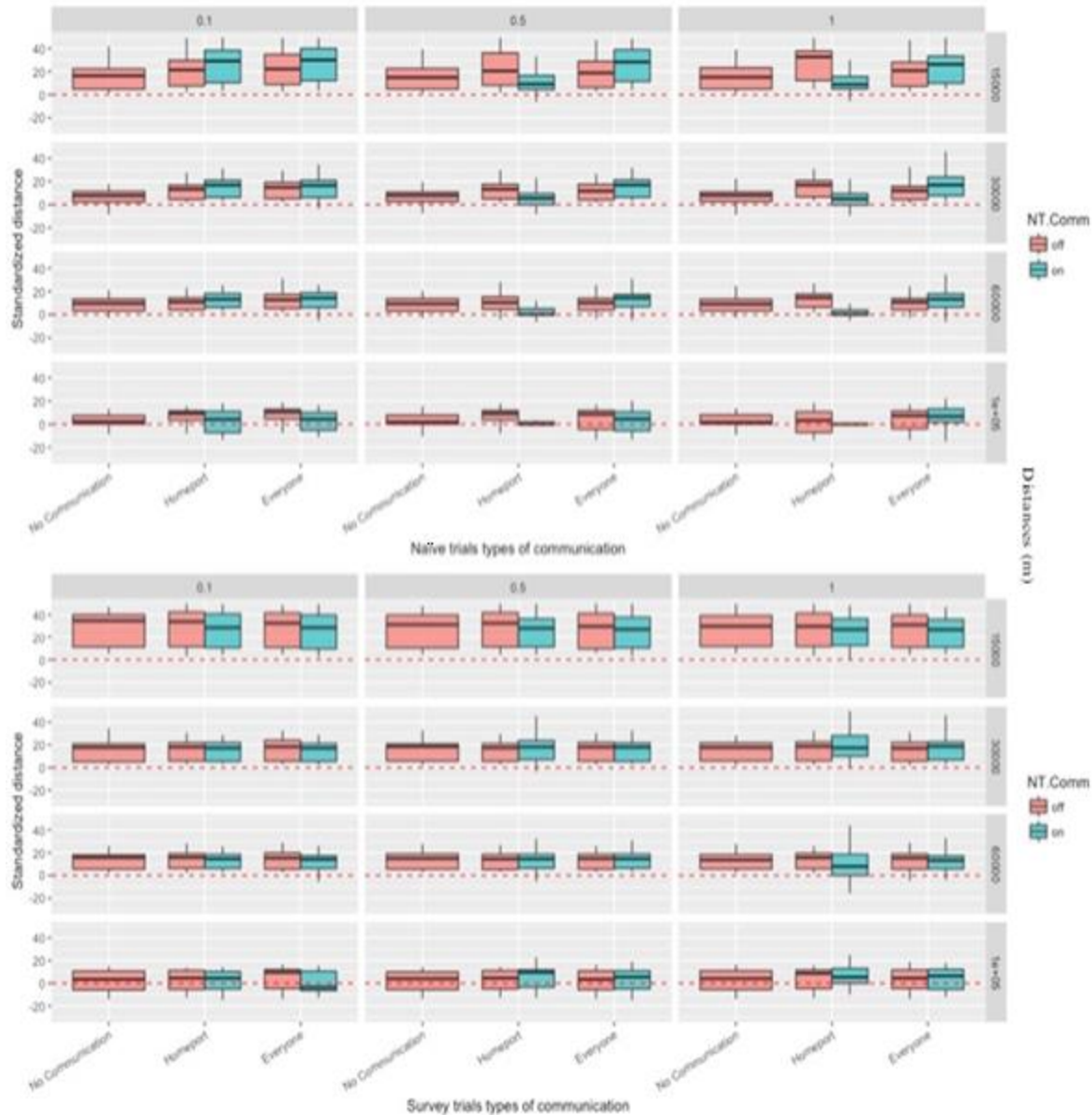
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1667 **Figure 3.9** The results of Ripley's K estimate for others-weight of 1 for the homeport
 1668 **communication trial.** This graph looks at associations among traditional vessels. The grey
 1669 **area shows the confidence envelope around Ho of a random distribution.** Within the grey
 1670 **area cannot be distinguished from a random distribution.** The red dashed line is the
 1671 **theoretical values of random distribution for the data (Ho hypothesis).** Anything above is
 1672 **significantly clustered while below is significantly dispersed.** This is how Ripley's K results
 1673 **were analysed for traditional, non-traditional and non-traditional/traditional associations**
 1674 **across all weights and each type of communication for both the naïve and survey trials.**

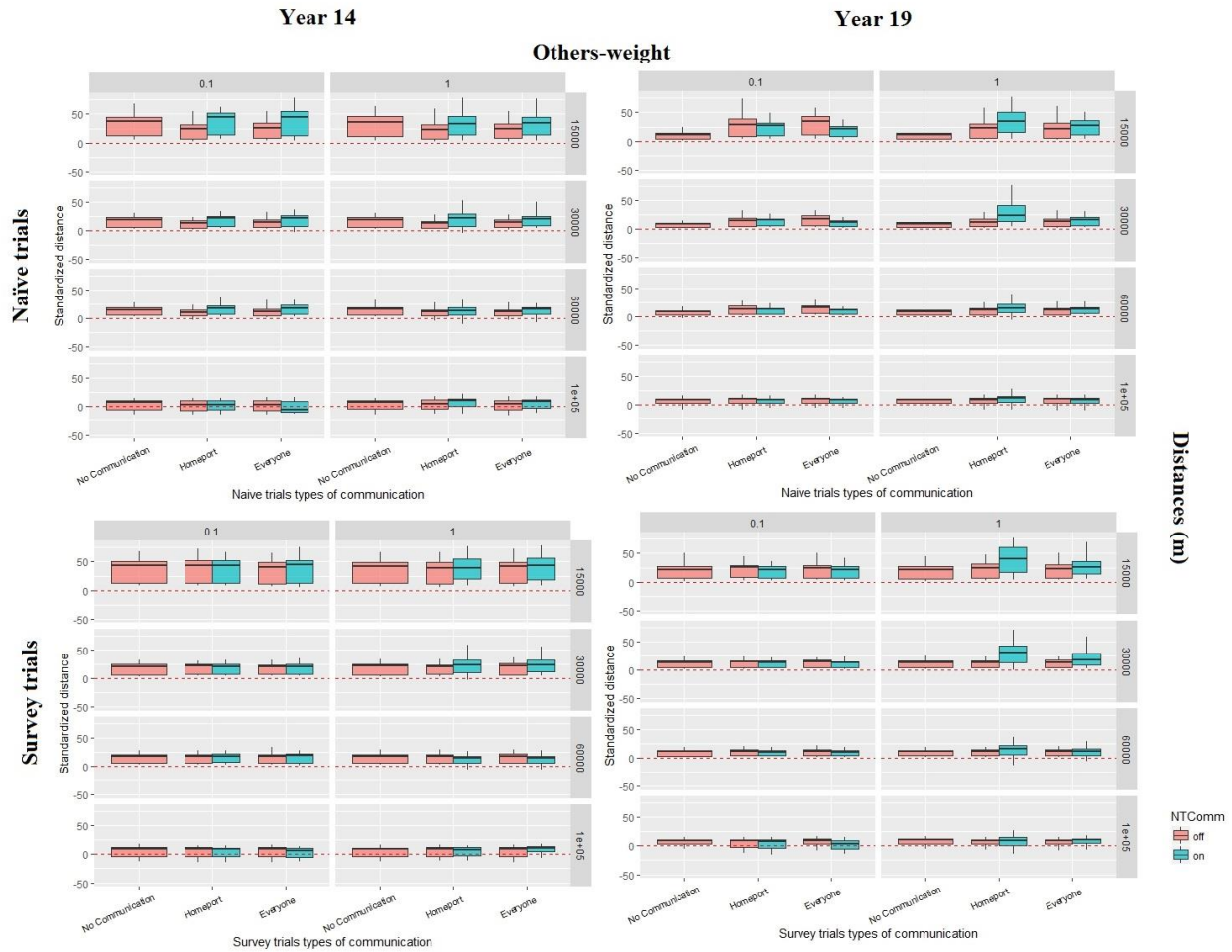
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1677 **Figure 3.10** The standardized Ripley's K value across the different weights, distances for
 1678 each type of communication tested and when non-traditionals are communicating and not
 1679 for the naïve and survey trials. Each standardized Ripley's K value is based on the whole
 1680 fleet regardless of the type of communication occurring and each box plot is each of the 25
 1681 years of data combined based on the snow crab pre-season distributions. Others-weight of
 1682 0.5 was dropped as it was not significantly different than others-weight of 0.1. On and Off
 1683 represent non-traditionals included in communication (on) and non-traditionals not
 1684 included in communication (off). Distance classes 75000, and 90000 m were dropped as the
 1685 associations were similar to 60000 m.

1686



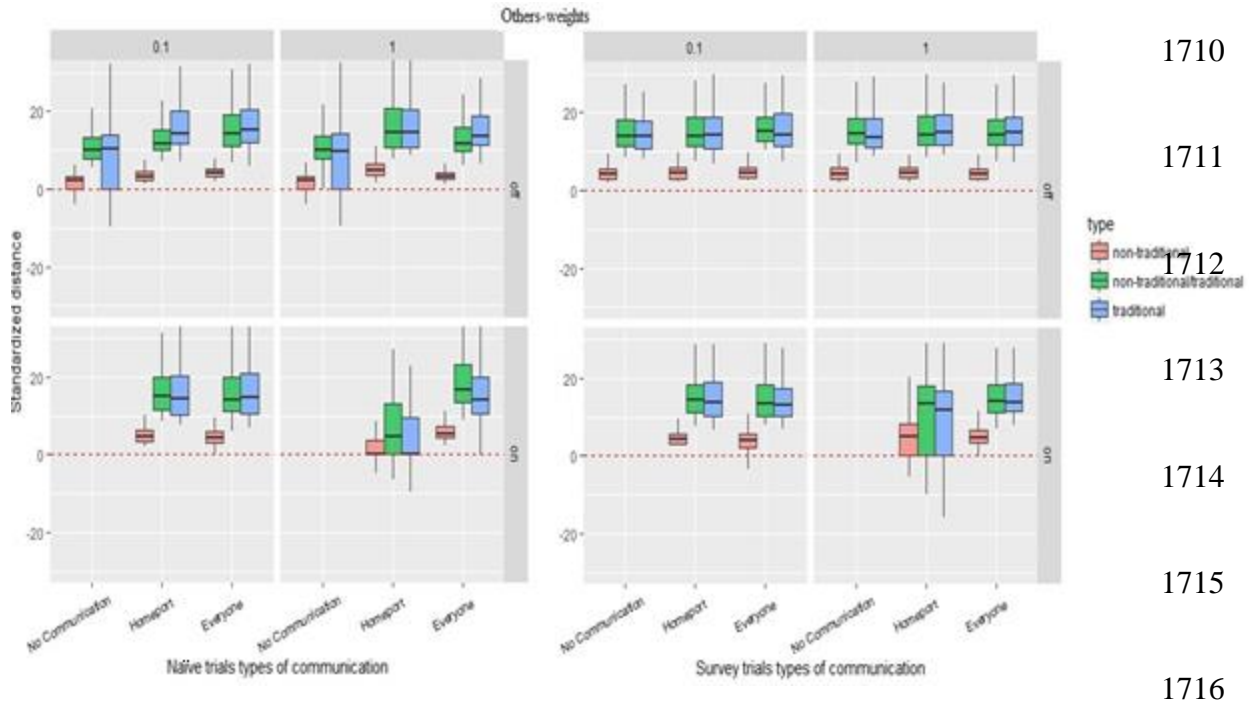
1687 **Figure 3.11** The standardized Ripley's K value across the different weights, distances for
 1688 each type of communication tested and when non-trationals are communicating and not
 1689 for the naïve and survey trials examining year 14 and 19. Each standardized Ripley's K
 1690 value is based on the whole fleet regardless of the type of communication occurring and
 1691 each box plot is each of the 30 replications combined based on the snow crab pre-season
 1692 distributions. Others-weight of 0.5 was dropped as it was not significantly different than
 1693 others-weight of 0.1. On and Off represent non-trationals included in communication
 1694 (on) and non-trationals not included in communication (off). Distance classes 75000, and
 1695 90000 m were dropped as the associations were similar to 60000 m.

1696

1697 Examining years 14 and 19 (high and low abundance) there were minor differences with
1698 associations being slightly higher than those observed in Figure 3.10 when non-trationals were
1699 included in the communication across all the different types of communication trials (Figure
1700 3.11)

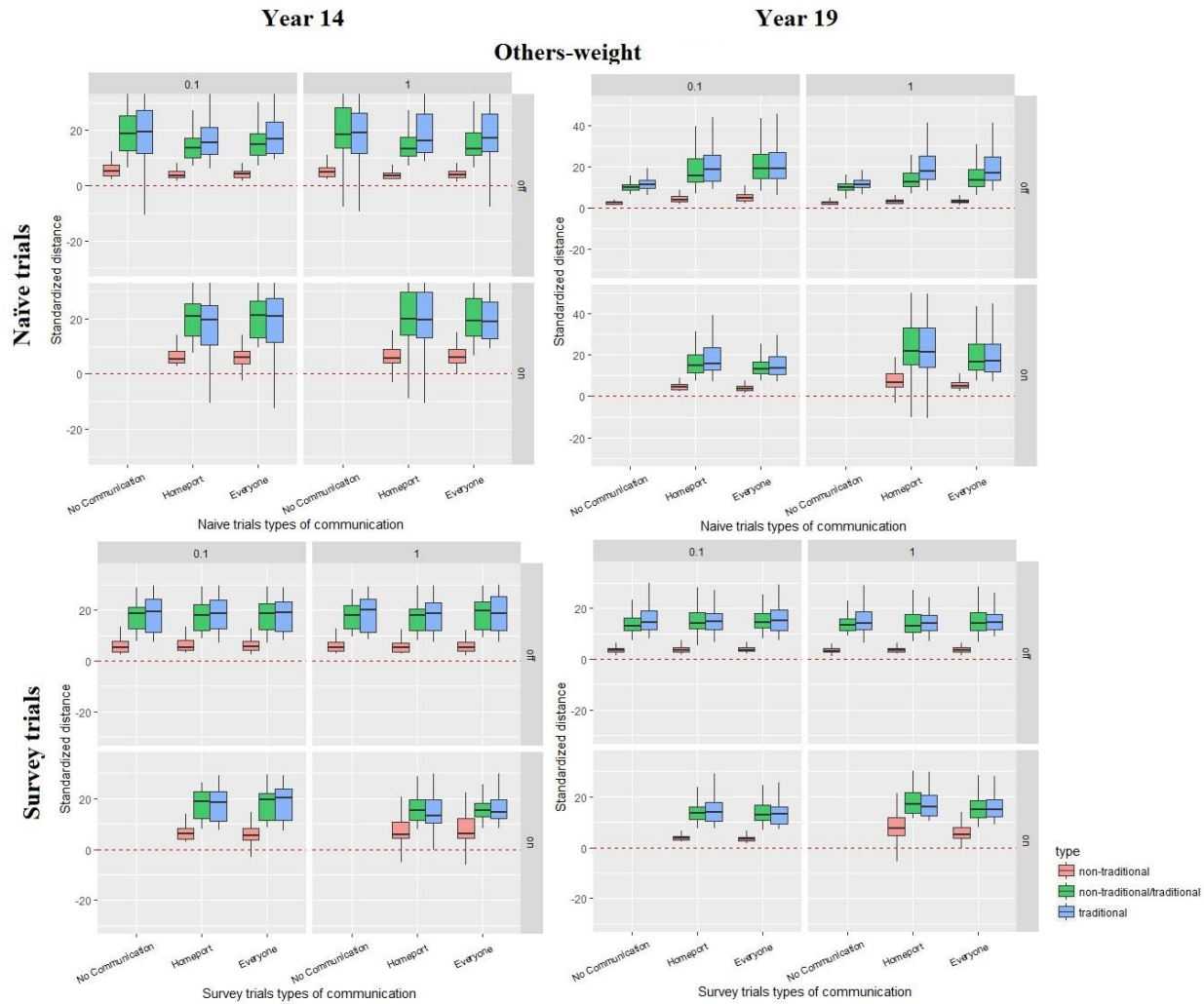
1701 Examining associations based on vessel type showed that there were always higher levels
1702 of clustering amongst the traditional vessels, next was amongst the traditional and non-
1703 traditional, and the lowest levels were observed between the non-trationals. When non-
1704 traditional were included in the communication there was more variability among the
1705 associations observed (Figure 3.12) although the pattern previously described did not change.

1706 The results from years 14 and 19 followed similar patterns to those observed in Figure
1707 3.12 where traditional vessels still had higher levels of associations, then the traditional and non-
1708 traditional vessels and the lowest levels being observed in the non-trationals vessels (Figure
1709 3.13).



1717 **Figure 3.12** The standardized Ripley's K values of each type of association across the
 1718 **different weights, types of communication and split into whether the non-traditional**
 1719 **vessels were communicating or not for the naïve and survey results. Each standardized**
 1720 **Ripley's K value is based on the whole fleet regardless of the type of communication**
 1721 **occurring and each box plot is each of the 25 years of data combined based on the observed**
 1722 **snow crab pre-season distributions. Others-weight of 0.5 was dropped as it was not**
 1723 **different from others-weight of 0.1.**

1724



1725

1726 **Figure 3.13** The standardized Ripley's K values of each type of association across the
 1727 different weights, types of communication and split into whether the non-traditional
 1728 vessels were communicating or not for the naïve and survey results for years 14 and 19.
 1729 Each standardized Ripley's K value is based on the whole fleet regardless of the type of
 1730 communication occurring and each box plot is each of the 30 replications combined based
 1731 on the observed snow crab pre-season distributions. Others-weight of 0.5 was dropped as it
 1732 was not different from others-weight of 0.1.

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1736 **Discussion**

1737 Across the naïve and survey results there is a general trend of clustering amongst vessels
1738 from the same homeport at the smallest distance. As distance increases, clustering decreases to
1739 random distributions at the middle distance classes and dispersal at the largest. These trends are
1740 similar to those observed in Chapter 2 of this thesis. The associations between traditionals were
1741 also the highest, among the two vessel types was slightly lower, while non-traditionals were
1742 mostly randomly distributed. These results support the hypothesis that there are varying levels of
1743 communication occurring in the snow crab fishery, but the complexity of pinpointing the exact
1744 levels of communication is difficult. Branch et al. (2006), and van Putten et al. (2011) stated that
1745 crew members who are related, friends or from similar homeports are more likely to share
1746 information and could explain the associations observed. In this model communication was
1747 happening at homeports and resulted in similar patterns to those observed in Chapter 2. It is
1748 difficult to measure communication in the snow crab fishery, in part because of the large number
1749 of vessels fishing across 86 homeports in four Canadian provinces. Monitoring radio and
1750 homeport communication is nearly impossible in the snow crab fishery; therefore incorporating
1751 the survey data from Chapter 2 and examining varying amounts of communication in an ABM
1752 allows an insight not available with the fishery data alone. There tended to be higher levels of
1753 associations when non-traditionals were included in the analysis. This suggests that at the
1754 extremes non-traditionals may be following traditional vessels more than in the more average
1755 abundance years.

1756 When there are high levels of communication occurring the model produces higher levels
1757 of clustering as long as the non-traditionals are not included except at the extremes of abundance
1758 in years 14 and 19. This is in agreement with results from Little et al. (2004), who found that

1759 information exchange amongst vessels led to more similar catch rates and profits between the
1760 different types of vessels or strategies. They suggested that with the two different fishing
1761 strategies most commonly seen – “Cartesian” (risk averse strategy) and “Stochast” (risk takers)
1762 from Allen and McGlade (1986) that one fishing strategy was also better than the other with
1763 different levels of communication. This was the case in this fishery as well. There were always
1764 higher levels of clustering when only the traditional vessels were communicating, and when non-
1765 traditionals were included associations were closer to random. Traditional vessels would benefit
1766 from communicating together, and wouldn’t benefit from communicating with non-traditionals.
1767 Non-traditionals would benefit from the traditional’s knowledge and experience in locating crab.
1768 This is supported by the lower levels of clustering observed when non-traditionals were included
1769 in the communication during the different trials but not that total landings results. The results
1770 from this chapter showed that total yearly landings were higher in the pre-season survey trial
1771 results among the different types of communication. The total yearly landings were more stable
1772 in comparison to the variation seen in the naïve trial results. These results are supportive of Salas
1773 and Gaertner’s (2004) findings that communication helps stabilize this uncertainty.

1774 Associations based on homeport location resulted in clustering at the smaller spatial
1775 scales, random at the middle distances and then dispersal at the largest spatial scales. This
1776 suggests that some vessels may be fishing in similar areas, while other vessels from the same
1777 homeport may have information on different areas and fishing elsewhere. This is consistent with
1778 assumptions from Little et al. (2004) that vessels from similar homeports may be “spying” on
1779 each other, and resulted in them clustering spatially and effort-wise. This may be the case in the
1780 GSL snow crab fishery as well. It is not to say that every single vessel from a homeport is
1781 communicating with each other, but that communication among these vessels is more likely.

1782 Actual communication patterns can be complex as there is variability amongst individuals on
1783 who they trust and are communicating with, and changes over time (An et al. 2005).

1784 During the naïve trials interesting patterns emerged during the no communication trials.
1785 There were higher landings in these trials, which may suggest that there may be negative
1786 implications to communication as well. When vessels communicate this may result in less time
1787 being spent exploring the fishery, and less chance of finding unexplored patches that may be
1788 highly productive. When vessels started a season with prior information on crab distribution it
1789 resulted in more reliable total landings across years whether vessels were communicating or not.
1790 When non-traditionals were included in communication amongst vessel crews, lower levels of
1791 clustering were also observed. It could be due to more vessels communicating resulting in a
1792 broader knowledge of the fishery and less need to fish in similar areas, but this may not be the
1793 case either. Since vessels had lower landings when everyone was communicating it could be the
1794 negative influence of non-traditionals in communication. Since non-traditionals have lower
1795 catchability than traditional vessels, they may be misinforming the traditional vessels. The non-
1796 traditionals may find an area to be unproductive, which may in fact be higher in snow crab
1797 abundance but they are just not as successful at fishing in these areas resulting in them
1798 misinforming the rest of their group. Also, if there are numerous vessels fishing this may deplete
1799 the patch quickly and may result in dispersion. The results of associations based on vessel type
1800 indicated that there were always higher levels of clustering of traditional vessels and amongst the
1801 two types than just the non-traditional vessels throughout every type of communication and
1802 whether they had survey knowledge or not. This would suggest that vessels who have lower
1803 catch rates have less knowledge to share and will communicate less with more successful
1804 vessels, as suggested by Salas and Gaertner (2004).

1805 During lower landing years, landings were not significantly different between naïve and
1806 survey trials though suggesting that having prior knowledge of the fishery in lower abundance
1807 years does not impact their catch rates. This could suggest that during years of lower abundance
1808 surveys are less helpful. This could be due to the lack of profitable sites and too many fishers
1809 trying to find them.

1810 Trends in homeport and vessel type associations are similar to those observed in chapter
1811 two. There are always higher levels of clustering amongst traditional vessels suggesting that they
1812 are communicating in some form. In this chapter, they are always communicating across trials
1813 other than no communication, and are found to have the highest levels of clustering supporting
1814 the hypothesis from Chapter 2 that traditional vessels have the highest levels of communication.
1815 Non-traditional vessels had minimal levels of clustering at the 30 km spatial scale but were
1816 mostly randomly distributed. These results are similar to chapter two as they mainly had random
1817 distributions, but this model did not capture observational learning which may play a role in
1818 information exchange while at sea (Vignaux 1996, Little et al. 2004). There was clustering
1819 amongst the two types, but mainly at the lower spatial distances, while in Chapter 2 the
1820 clustering increased with increasing distance. This again could be a result of observational
1821 learning not being correctly modelled in this ABM, and could be expanded in the future. Overall
1822 this model confirms that increasing levels of communication causes aggregation at smaller
1823 spatial scales, but does not explain the trends observed in Chapter 2 at larger spatial scales. The
1824 scales are different between chapters and could be a cause for the differences. Overall, this
1825 model is a first step in the direction for management purposes, but will need more informative
1826 communication rules.

1827 It is difficult to monitor communication in fisheries, as relationships are fluid and change
1828 over time and between individuals (Salas and Gaertner 2004, An et al. 2005). This model has set
1829 rules for every individual, but in reality this is not the case. An ABM can be used to model
1830 different types of communication, although with the limited rules applied to this model, it lacks
1831 the complexity of the actual fishery but gives a broad insight into the possibilities, and has
1832 potential to be expanded. Without directly observing communication and information exchange
1833 in the fishery, such as in Palmer (1991) who monitored radio and dock communication, or
1834 interviews as done in Little et al. (2009), the accuracy of this ABM is limited. With advancing
1835 technology, cell phones (Foss and Couclelis 2009) are an important form of communication to
1836 consider as well, and were found to have significant impacts on effort allocation in the Kerala
1837 fishery of southern India. Further research could be done into the possible forms of
1838 communication in the GSL snow crab fishery, using similar methods mentioned, providing more
1839 flexible rules to the model. Communication could become more fluid in future models to
1840 represent evolving levels of information exchange, based on whether or not a vessel was
1841 successful and would remain in the communication group. Vignaux (1996) stated that many
1842 vessels tend to not be risk takers in order to maintain higher catch rates in relation to the rest of
1843 the fleet to keep their social standings, and could be something to consider when creating groups.
1844 This could be done so that if a vessel was unsuccessful they were no longer a part of the group.

1845 Another limitation to this model is the spatial resolution. In the fishery, locations are
1846 exact, while the model is based on 10x10 minute squares resulting in the coarse resolution of the
1847 analysis. This would prevent some of the small-scale associations observed in Chapter 2 to be
1848 tested for in this model and explain the differences between chapters at the larger scales.

1849 The current ABM lacks some biological and economical aspects of the fishery. In the
1850 future, other variables such as the price of crab could be incorporated, which could be impacting
1851 how vessels fish, and their strategies especially during years of fluctuating abundance, based on
1852 similar conclusions from Dupont (2000) in British Columbia's salmon fishery. Incorporating
1853 realistic fuel prices could also impact the distribution of vessels. Bernstein et al. (1991)
1854 suggested that as travel costs become larger, the predators (or the vessels in this case), may have
1855 less desire to fish further away from their homeports or leave their current patch. Little et al.
1856 (2004) suggested that vessels from certain homeports may be further from productive areas and
1857 have a more difficult time getting there, or be limited by the price of fuel. This may be influential
1858 on associations observed, or there may be similar association results, just in patches closer to
1859 their respective homeports. Another aspect that could be included in the model, is implementing
1860 total allowable catch or individual quotas (Little et al. 2009). In the fishery when abundance is
1861 low, the quotas are lowered to match this and could impact how vessels fish. If vessels are
1862 getting close to their quota their fishing strategies may change and they may be more likely to
1863 fish in lower abundance areas (E. Wade, Gulf Fisheries Centre DFO, Moncton, Canada, personal
1864 communication, 2016). Incorporating changing fishing strategies, both short and long-term into
1865 the model may capture more of the complexity of the real fishery (Little et al. 2004).

1866 Catch and effort have historically been used to monitor abundance in stock assessments,
1867 but models have now shown that catch and effort data alone are not sufficient indices to predict
1868 abundance trends (Peterman and Steer 1981, Bannerot and Austin 1983, Walters and Maguire
1869 1996). This is because fleet behaviour, or fishing strategies, may allow vessels to maintain
1870 productive catch rates and high CPUE even though the fish abundance is decreasing (Hilborn
1871 1985, Vignaux 1996). Dorn (2001) suggested that instead of ignoring CPUE it is best to combine

1872 it with experience, and fishing behaviour to predict trends in abundance and create a new
1873 approach to monitoring population trends, such as using an ABM (Hilborn and Walters 1987,
1874 Little et al. 2004, Little et al. 2009). Furthermore, by examining fleet behaviour, it may help
1875 improve communication between fisheries scientists and the fishing industry by recognizing the
1876 importance of fishing experience and its impacts on management.

1877 Examining where and how fishers allocate effort is a crucial step in management
1878 decisions and is directly linked to communication and fleet dynamics. Future steps could
1879 incorporate stricter rules for observational learning, which is likely a major influence in the snow
1880 crab fishery based on the findings from Chapter 2 of this thesis, of clustering amongst the
1881 different types of vessels (Vignaux 1996). Little et al. (2004) stated that fisher's choice of a
1882 fishing location is not only based on their perceived catch from that area, but also on
1883 observations of what other vessels have caught in that area as well.

1884 This model has the potential to be useful for management purposes and modelling the
1885 different implications on catch, revenue, and snow crab abundance. The model could incorporate
1886 more information and then implement common management strategies such as grid closures,
1887 total allowable catch, individual quotas, and number of licences (Dorn 1997, Little et al. 2009,
1888 Gao and Hailu 2012). It would also be interesting from a management perspective, if a patch is
1889 deemed to be productive, to monitor how many vessels fish there at the same time throughout the
1890 season, and the impact on final abundance in that patch. Is the patch over-fished or will there still
1891 be enough snow crab for the upcoming seasons? A study by Ahearn et al. (2001) found in an
1892 ABM for tiger and human interactions, that tiger populations are sustainable at low human
1893 densities, but when human population increases past a certain extent, the tiger population
1894 decreases significantly. This could be a future key aspect added to the current ABM to see what

1895 density of clustered vessels will decrease the grid abundance beyond a recovery point. This could
1896 aid in predicting future snow crab populations and would be a useful tool for management and
1897 fishers.

1898 An ABM could be a useful tool for many fisheries that are not as well managed as the
1899 snow crab fishery. Lempert (2002) stated that ABMs are useful tools to help develop policy-
1900 making or management protocol when other models are not as successful at predicting social
1901 processes, and have been used in social science in the public and private sectors. The interactive
1902 interface with “real time” graphics make ABMs like mine, useful as a communication tool
1903 among scientists, managers, and fish harvesters. It could allow predictions to be made based on
1904 different strategies or levels of communication. The interface provides quick and easy
1905 adjustments that can even be altered with each time step. It provides a visual representation of
1906 the fishery to show fishers what exactly is happening at the large scale rather than the limited
1907 perception they have while at sea. Overall, this agent-based model was the initial step in
1908 capturing the variability of communication in the snow crab fishery, and could be developed into
1909 a tool to represent fleet dynamics when evaluating different management protocols.

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2084 **Chapter 4 - Conclusion**

2085 The focus of my thesis has been to evaluate vessel dynamics in the Gulf of St. Lawrence
2086 (GSL) snow crab (*Chionoecetes opilio*) fishery and the impacts of communication on effort
2087 allocation and total yearly landings. Presently, catch per unit effort (CPUE) is the standard
2088 method in evaluating population abundance across many fisheries. The problem with only
2089 examining CPUE (Peterman and Steer 1981) is that fleet behaviour may allow vessels to
2090 maintain relatively high catch and CPUE even with declining fish abundance (Hilborn 1985).
2091 Therefore, the importance of including fleet behaviour in population assessments is critical to
2092 ensure effective management strategies. The limiting issue is the lack of research on vessel
2093 dynamics across many fisheries (Hilborn 1985, Salas and Gaertner 2004, Branch et al. 2006).

2094 My goals were to examine spatial associations in the GSL snow crab fishery which may
2095 be the result of communication. I was unable to measure communication directly in the fishery,
2096 although examining the resulting spatial associations gave insight into the possible levels of
2097 communication. This was accomplished by examining associations of the fishery in Chapter 2
2098 based on homeport location and vessel type and then modelling the varying levels of
2099 communication using an agent-based model (ABM). By effectively combining the two chapters,
2100 I hoped to infer what levels of communication were occurring, so in the future these interactions
2101 could be applied to management strategies.

2102 There was minimal clustering amongst vessels from the same homeport in the fishery.
2103 The levels of clustering observed from the ABM remained higher, and suggests that the
2104 clustering of vessels from the same homeport may be a complex process in real life. In the ABM
2105 even with the lower levels of communication, clustering remained higher, although when
2106 everyone (non-traditional and traditional) were communicating, the levels were closer to the

2107 actual observed values in the fishery. This suggests that vessels from the same homeport may
2108 communicate broadly. Since most homeports were made up of the two types of vessels, there
2109 may be communication happening among certain individuals within a homeport that is more
2110 likely to occur among the traditional vessels. With their longer experience in the fishery, their
2111 long-term investment and the higher chance of them knowing each other (Branch et al. 2006, van
2112 Putten et al. 2011), they may be communicating more than any non-traditional vessel. There are
2113 generally more traditional vessels at each homeport, which may explain why we are observing
2114 clustering, but lower levels. Certain traditional vessels from the homeports may cluster while the
2115 other vessels are left to explore on their own and fish away from the clustered vessels. This
2116 would result in an overall clustering pattern but lower than if almost every vessel was
2117 communicating (as observed in Chapter 3).

2118 The clustering observed between the traditional vessels in both Chapter 2 and Chapter 3
2119 suggests that the homeport associations observed are likely due to the clustering of traditional
2120 vessels. There is always clustering of traditional vessels in both chapters, and Chapter 3 always
2121 accounted for them communicating across trials. They were still clustered even in trials of no
2122 communication which may also suggest that even if traditionals may not be sharing information,
2123 their experience may cause them to fish in similar areas (areas they know to be productive). This
2124 is something for management to consider, that since traditional vessels have higher catches, and
2125 are clustering in certain areas, this may cause patches to be depleted quicker than anticipated and
2126 may not only affect that patch's abundance the next year, but surrounding patches as well.

2127 There is also a clustering of the two types of vessels, suggesting that since non-
2128 traditionals are not likely communicating due their mostly random distributions, they are
2129 following successful traditional vessels and fishing in similar areas. This again, would cause

2130 many vessels to be fishing in similar areas having detrimental impacts on those area's
2131 abundance. Knowing that non-traditional vessels are trying to improve their catch rates by
2132 following traditional vessels could allow future models to determine how many vessels of both
2133 types can fish in an area before that patch is depleted beyond recovery. This could help
2134 determine how many non-traditional licences can be distributed each year based on overall snow
2135 crab abundance and even as small scale as grid abundance.

2136 Models also suggest that total landings will always be higher when the vessels are given
2137 the pre-season survey information, and could be something to consider in the future. This could
2138 help avoid clustering and force certain vessels to explore other areas. As catch rates were higher
2139 in the beginning of the season, a different management approach could be to decrease the amount
2140 of licenses given out at the beginning of the season, monitor catch rates, and if they are low
2141 enough in comparison to abundance, give more licenses out as the season progresses.

2142 It was insightful to combine Chapter 2 and 3 together using an empirical approach to
2143 contrast what was actually occurring in the fishery (Chapter 2), and possible explanations for
2144 these patterns (Chapter 3). With the lack of research into most fisheries vessel dynamics, taking
2145 both approaches allows one to model possible forms of communication, the extent, and the
2146 impacts on the environment and fish stock. This is not possible by only using one or the other,
2147 but the combination of using both spatial analysis and ABMs. One can speculate about the
2148 possibilities but without modelling what biologically and socially could be occurring, it is
2149 difficult to determine the levels of communication. If more biological and economic information
2150 on the snow crab fishery could be added to the ABM, this could provide even clearer
2151 communication possibilities and the resulting spatial patterns. Communication is complex and is
2152 difficult to capture in an ABM without stricter rules and more information from the fleet

2153 themselves. Future research could involve monitoring radio communication as done in Palmer
2154 (1991), or interviews (Little et al. 2009) for further insights into the role communication plays in
2155 the spatial distribution of vessels.

2156 There have been other studies that focused on modelling different management strategies
2157 in fisheries by incorporating fleet dynamics. Little et al. (2004) used a Bayesian approach to
2158 explore the effects of information exchange and found that communicating impacted effort
2159 allocation and resource exploration. Other studies (Dorn 1997, Gao and Hailu 2012) have
2160 examined common management strategies such as grid closures, total allowable catch, individual
2161 quotas and how many licenses are given out. Incorporating an ABM approach to examining fleet
2162 dynamics was able to give management a new perspective into the fisheries.

2163 The snow crab fishery is one of eastern Canada's most profitable fisheries and needs to
2164 be protected, to ensure long-term survival of the fishery and the snow crabs. The fishery employs
2165 many people each year as fishers, managers, and processors. The livelihoods of hundreds of
2166 people depend on this fishery, therefore it is crucial to continue monitoring spatial associations
2167 and fleet behaviour to incorporate this information with catch per unit effort for effective
2168 management strategies. Using only one tool to help solve the complexities of the fishery will
2169 always provide ineffective management strategies. This fishery is an ideal system to continue
2170 monitoring due to the already effective collaboration between management and the fleet. The
2171 snow crab population is on a slow and steady decline (DFO 2016) and both sides of the fishery
2172 (management and the fleet) want to maintain a sustainable stock for future generations. For this
2173 reason the fleet may be more inclined to provide insights into their communication than other
2174 fisheries that lack a history of strong collaborations (Loch et al. 1995). This would provide the
2175 ABM with stricter communication rules. By continuing to monitor the snow crab fishery's fleet

2176 dynamics it will provide more representative ABMs that have the potential to be useful for
2177 management purposes in the near future.

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