THE ANALYSIS OF TEMPORAL AND ENVIRONMENTAL INFLUENCE ON COMMERCIAL CATCH RATE OF YELLOWTAIL FLOUNDER (LIMANDA FERRUGINEA)

EMMA G. POSLUNS

The analysis of temporal and environmental influence on commercial catch rate of yellowtail flounder (*Limanda ferruginea*)

by

©Emma G. Posluns

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Abstract

For the commercial fishing industry, efficiency and sustainability are key aspects of business. Knowing when and where to harvest, along with the environmental traits associated with good fishing grounds, minimizes costly fuel and time spent searching for fish. Quantifying this knowledge not only creates a baseline of habitat information, but also preserves fishing patterns for use by future harvesters or in developing fisheries. This study investigates temporal and spatial patterns in the catch rates of yellowtail flounder (*Limanda ferruginea*) recorded by factory freezer trawlers operating on the Grand Bank of Newfoundland and Labrador, Canada. The temporal analysis revealed that commercial catch rates are higher at night as well as during winter and summer. The findings suggest that ambient light levels and environmental factors are important for successful yellowtail flounder – trawl interactions. Spatial analysis is used to show the interactions between environmental variables and yellowtail flounder catch rates. It was found that wind speed, water depth, sediment type, and bottom water temperature all relate to catch rate, but in varying degrees. The results of this project provide evidential support for improved data collection, storage, and analysis by our industry partner.

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Chapter 1: Introduction and Overview

1.1 Yellowtail Flounder

The yellowtail flounder (*Limanda ferruginea*) is a ground-fish found in the western North Atlantic whose habitat ranges along the continental shelves between Labrador and Chesapeake Bay, the commercial concentrations of which reach a northern limit on the Grand Bank off the coast of Newfoundland and Labrador, Canada (Bigelow and Schroeder, 1953; Walsh, 1992). Additional distinct stocks exist on Georges Bank and Cape Cod, off Southern New England (Cadrin, 2010). Yellowtail flounder are a shallow water species found at depths between 40 – 100 m in sandy, muddy, or gravelly-sand substrate (Walsh, 1992). In this habitat yellowtail flounder, a small-mouthed pleuronectid, feed on benthic invertebrates including polychaetes, amphipods, small crustaceans and very small fish (Bigelow and Schroeder, 1953; Pitt, 1976). The species can tolerate water temperatures between -1 to 7°C, but they are generally found between 3 to 5 °C (Pitt, 1970; Walsh, 1992). Sexual maturity is reached at age five for males and age 6 for females; furthermore, spawning occurs between May and September, but peaks in late June (Pitt, 1970). While spawning has never been witnessed, the concentration of adult and juvenile flounder on the shallow Southeast Shoal hints that this region may be the most important spawning and nursery grounds on the Grand Bank (Frank et al., 1992; Walsh, 1992; Walsh et al., 2004).

Lying to the Southeast of Newfoundland, the Grand Bank is a raised marine plateau jutting into the Atlantic Ocean (Fig. 1.1). The Bank, which is characteristically flat and shallow, has water depths ranging from 30 to 190 m (Walsh et al., 2006; Kulka, 2009). Water properties are largely influenced by the Labrador Current, which provides sub-zero temperature polar water. Secondarily, the Grand Bank is influenced by warmer waters from the Gulf Stream (Helbig et al., 1992).

1.2 Newfoundland Commercial Yellowtail Flounder Fishery

The establishment of an international fishery for yellowtail flounder in the 1960s launched the commercial importance of this species in Newfoundland (Brodie et al., 2010); it had already been commercially significant off Southern New England since the 1930s (Cadrin, 2003). In Atlantic Canada the fishery had a slow start, but quickly grew into a profitable endeavor with the Total Allowable Catch (TAC) peaking in 1973 (Brodie et al., 2010). In the late 1980s to early 1990s catches were not properly reported by Canadian and foreign vessels, but surveillance estimates suggested they were exceeding the TAC (Fig. 1.2). Additionally, inadequate size and age sampling was taking place resulting in an indeterminate amount of undersize and juvenile yellowtail flounder being harvested (Brodie et al., 1993; Brodie et al., 1994). Total stock collapse lead to a moratorium in 1994 for the directed fishing of yellowtail flounder, which lasted until August 1998; by that time the species had recovered enough to support a commercial industry again.

Today the yellowtail flounder fishery is prosecuted in the Northwest Atlantic Fisheries Organization (NAFO) Divisions 3LNO, where it constitutes a 16 500 t quota and represents significant revenue to Ocean Choice International (OCI), the fishery's leading company. OCI has operated within the industry since 2007 when it purchased a majority of company shares from the former owners, Fishery Products International (FPI). FPI was a vertically integrated company created in the 1980s by consolidating a variety of inshore and offshore fishing companies in Newfoundland. Dedicated to the fishery with four offshore factory stern trawlers (>100 ft), OCI has over 90% of Canadian yellowtail flounder quota, employs skilled Newfoundlanders, and contributes to rural economies in the province.

The recovery of the yellowtail flounder stock provides a unique opportunity to observe a resilient population in a habitat shared with other less resilient species; American plaice (*Hippoglossoides platessoides*), Atlantic cod (*Gadus morhua*), and witch flounder (*Glyptocephalus cynoglossus*) also collapsed in the early 1990s on the Grand Bank, but these stocks have yet to be removed from fishing moratoriums. American plaice, which shares much of its habitat on the Grand Bank with yellowtail flounder, may be caught as bycatch, however, a strict 15% annual limit is enforced (NAFO, 2011). Subsequent avoidance of this species often leads to increased catch of smaller yellowtail flounder (28 – 35 cm; NAFO minimum legal length is 28 cm) which, due to economic reasons, are transported to China instead of being processed in Newfoundland, resulting in processing plant closures and the loss of local jobs. Pressure to harvest profitably sized fish while avoiding bycatch puts a strain on captains to steam for long periods of time searching for optimum fishing grounds, burning costly fuel in the process. The Grand Bank yellowtail flounder fishery, which has recently been awarded

Marine Stewardship Council certification, is increasingly invested in performing efficiently and sustainably.

1.3 Temporal and Environmental Effects on Commercial Fisheries

Industry will be more economic and environmentally sustainable by maximizing efficiency when locating and harvesting yellowtail flounder. One way to achieve efficiency is by quantifying patterns in the fishery, including when and where catch rates are high, and the environmental attributes associated with these locations. Catchability is related to the availability and vulnerability of a species to capture (Parrish, 1963), both of which depend on fish behaviour and trawl efficiency (Walsh, 1991). Time of day, season, and environment are among the factors impacting fish behaviour and trawl efficiency (Laevastu and Favorite, 1988), and consequently catchability. Ambient light levels on the seafloor due to time of day and season have been shown to impact fish behaviour in response to trawl interaction (Glass and Wardle, 1989; Ryer and Barnett, 2006). Scientists found low-light conditions, such as at night, have a positive effect on catch rate for many species including yellowtail flounder (Walsh, 1991).

Environmental factors also influence fish behaviour and trawl efficiency; understanding environmental impacts on commercial fisheries is increasingly more important and difficult to do given our current changing climate. It is important for industry to have a baseline of knowledge related to fish and environmental interaction, and to monitor changes in these interactions to maintain a sustainable, long-term fishery.

Past research has shown that fish catchability is affected by wind speed, bathymetry, sediment type, and water temperature among other factors (Harden Jones and Scholes, 1980; Walsh et al., 2004; Politis et al., 2012). Vulnerability of some marine species is impacted by increasing wind speed and thus turbidity; turbulence may reduce visibility so that individuals cannot detect and avoid the trawl mouth (Perry et al., 2000). Ocean bathymetry affects fish vulnerability to capture by changing net geometry and efficiency; for example, varying fishing depths during a tow leads to less contact between the footrope and seafloor and a greater chance that fish will escape from a trawl (Queirolo et al., 2012). Bathymetry also affects availability of fish by influencing their habitat. Sediment type impacts fish availability by affecting feeding habits and predator-prey interactions; certain sediments, like large rocks or boulders, also provide safety for juvenile and adult fish (Walsh, 1992; Simpson and Walsh, 2004). Lastly, water temperature is known to affect vulnerability of fish to approaching trawls. This factor is generally thought to impact both the response threshold and swimming capability of fish, which enhances herding capabilities in the mouth of a trawl (see Winger et al., 2010a for review). These environmental variables change on multiple temporal scales ranging from diurnal to seasonal to decadal; therefore, the decision of when and where to fish becomes increasingly complicated.

The complex temporal and spatial patterns that make up an ecosystem are part and parcel of a captain's ecological knowledge of his/her fishery. In order for this knowledge to be shared with new captains, used in developing fisheries, or analyzed by scientists for information on stock abundance, we must first collect relevant environmental data and quantify the patterns in commercial fisheries. Analyzing the relationships between catch rate and temporal and environmental variables is one of many steps that can lead to a more efficient and sustainable fishery, one that is less reliant on fossil fuels for lengthy trips in search of fish. Collection, storage, and usage of *in situ* data including ambient light level near the seafloor, sea state, bathymetry, sediment type, and bottom water temperature will help in building a holistic understanding of yellowtail flounder and how to harvest them.

1.4 Thesis Outline

The objective of this study was to investigate the impacts of temporal and environmental variables on commercial catch rates of yellowtail flounder. Variables of interest included temporal factors (i.e., time of day and season) and environmental factors (i.e., wind speed, water depth, substrate type, and bottom water temperature). Separate analyses were conducted for each of these two distinct groups of variables.

In the first experimental chapter (Chapter 2) I investigated the effects of time of day and season on catch rate using classical statistics. This project aimed to quantify catch rates in order to give objective results on when the highest catch rates occurred during the study period. This task was completed using one and two-way Analysis of Variance tests and t-tests. Results showed that the highest seasonal catch rates occurred in winter and summer during nighttime. I discuss possible reasons for these findings as well as implications for industry.

In the second experimental chapter (Chapter 3) I examined the relationships between catch rate and environmental variables using spatial statistics. The goal of this project was to use Geographically Weighted Regression analysis, an innovative tool for analyzing local spatial variation, to examine and quantify the environmental factors influencing commercial catch rate of yellowtail flounder. Results showed that catch rates had negative relationships with wind speed (i.e., as wind speed increased, catch rate decreased), positive relationships with water depth in spring and summer (i.e., as water depth increases, catch rate increases), and negative relationships with water depth in fall (i.e., as water depth increases, catch rate decreases). I found conflicting relationships between water depth and catch rate in winter for both vessels; during this season other variables may be more statistically significant. Substrate type was the least statistically significant variable. Catch rate showed positive relationships with bottom water temperature in winter, but relationships were less clear in other seasons. The results of this chapter were synthesized and discussed with respect to their impacts on this important commercial industry.

The final thesis chapter summarizes the temporal and environmental experiments, discusses the benefits and limitations of both studies, and proposes suggestions to industry for future projects in this area.

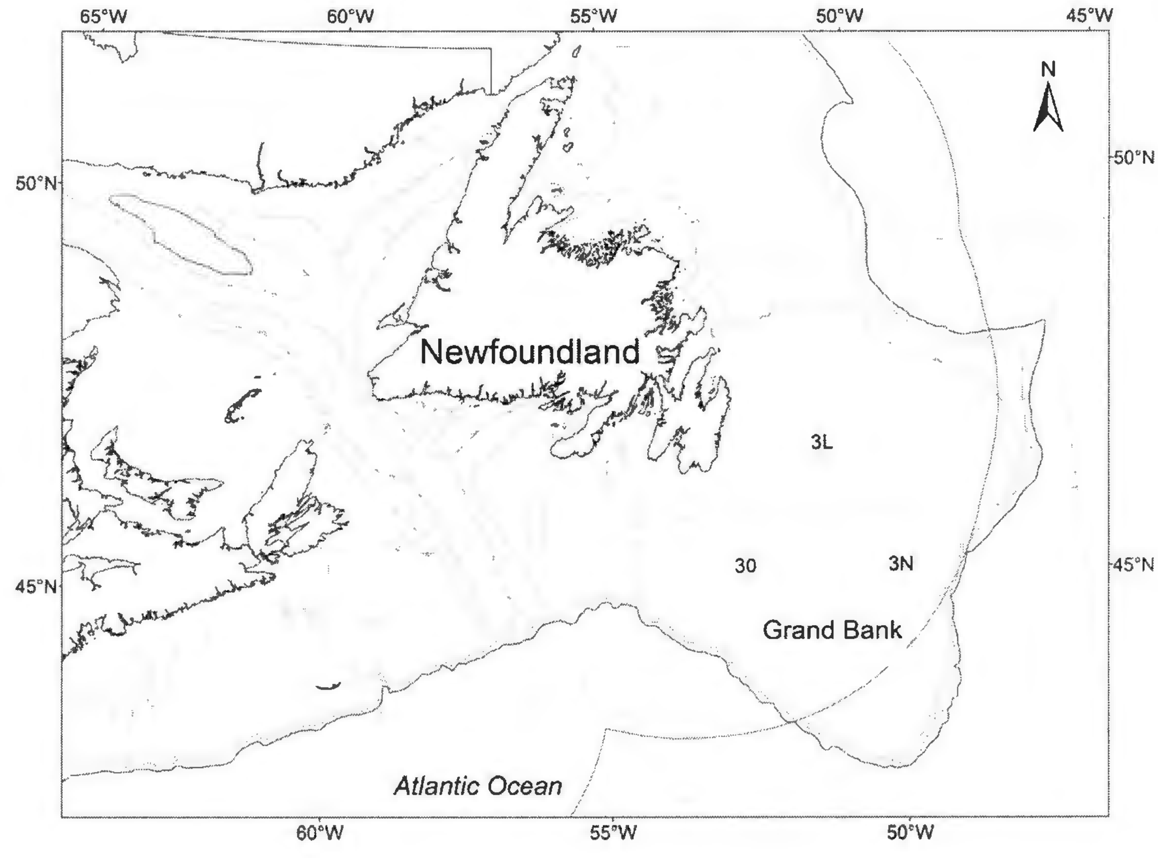

Figure 1.1: Map of the study area. NAFO Div. 3LNO are located partially within the exclusive economic zone (EEZ), shown by the curved line.

Catch (split in Canadian and non-Canadian) and TAC of yellowtail flounder in NAFO Divisions 3LNO.

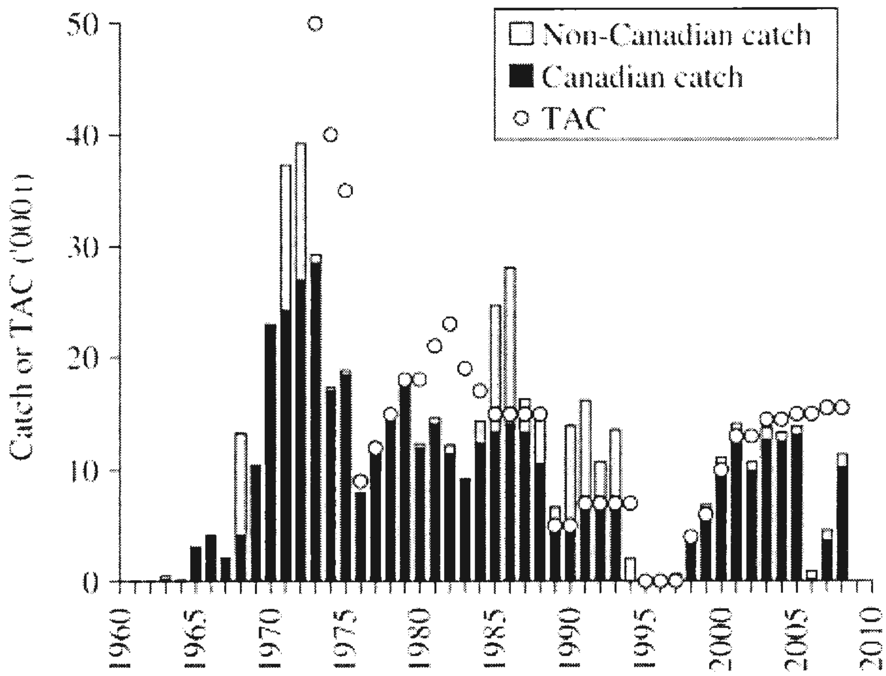

Figure 1.2: Canadian and non-Canadian catch and total allowable catch (TAC) of yellowtail flounder in NAFO divisions 3LNO between 1960 and 2010 (Brodie et al., 2010).

Co-authorship Statement

I am the principal author of all chapters presented in this thesis. I was responsible for the planning, research, data analysis, interpretation and manuscript preparation. Dr. Paul Winger and Randy Gillespie are co-authors on chapters 2 and 3. They provided significant help in the form of guidance, academic feedback, and editorial review.

The following two chapters (chapter 2 and 3) will be submitted separately as manuscripts to scientific journals. They follow the citation style of *Fisheries Research.*

Chapter 2: Seasonal and diurnal effects on commercial catch rate of yellowtail flounder (*Limanda ferruginea*) on the Grand Bank of Newfoundland

Abstract

Diel and seasonal variation in catch rate of yellowtail flounder (*Limanda ferruginea*) were analyzed using commercial vessel logbook data from the Grand Bank, Newfoundland and Labrador, Canada. Data from two vessels, the *F/V Mersey Viking* (1224 tows) and the *F/V Aqviq* (1612 tows) were used in this study. Temporal data were compared using one and two-way Analysis of Variance tests and t-tests. Season and time of day significantly affected catch rate for both vessels. Daytime catch rates for the *Mersey Viking* were significantly higher in winter and summer (mean: 14.15 kg/min and 16.50 kg/min, respectively vs. spring: 9.02 kg/min, fall: 11.35 kg/min). Nighttime catch rates for the *Mersey Viking* were higher in winter and summer, though it was not always statistically significant (mean: 15.72 kg/min and 16.67 kg/min, respectively vs. spring: 8.64 kg/min, fall: 13.67 kg/min). Daytime catch rates for the *Aqviq* were significantly higher in winter and summer (mean: 16.18 kg/min and 18.02 kg/min, respectively vs. spring: 12.40 kg/min, fall: 11.19 kg/min). Nighttime catch rates for the *Aqviq* were significantly higher in winter and summer (mean: 18.26 kg/min and 19.32 kg/min, respectively vs. spring: 12.38 kg/min, fall: 12.78 kg/min). Both vessels revealed higher catch rates at night, though these results were not always statistically significant. The

results are discussed in relation to possible changes in availability and vulnerability of yellowtail flounder to trawl capture.

2.1 Introduction

The efficiency of a bottom trawl to capture fish is known to be affected by many factors related to vessel operations, gear technology, the availability of fish, and their vulnerability to capture once in the path of a trawl (Glass and Wardle, 1989; Walsh, 1991; Casey and Myers, 1998; Petrakis et al., 2001; Ryer and Barnett, 2006; Ryer, 2008). Factors affecting fish behaviour and therefore their vulnerability to capture are numerous (see review by Winger et al., 2010a). Since the 1960's, researchers have used various techniques, including underwater camera systems at sea (Blaxter et al., 1964; Glass and Wardle, 1989; Underwood et al., 2012), laboratory observations of captive animals (Blaxter et al., 1964; Ryer and Barnett, 2006), and the analysis of trawl catch (Beamish, 1966; Casey and Myers, 1998; Petrakis et al., 2001) to determine the role and influence of different factors on fish behaviour and subsequent trawl capture.

Industry, government, and academia all benefit from the understanding of fish and gear interactions. Knowledge of fish behaviour in response to trawls can lead to gear modifications that greatly improve capture efficiency and reduce ecological impacts such as bycatch, seabed impacts, and fuel consumption/carbon footprint (Olla et al., 2000; Hannah et al., 2005). Research surveys designed to estimate population abundance will have unknown biases if fish distributions and availability to gear are unknown (Walsh, 1988; Casey and Myers, 1998). When fish and gear interact, trawl technology aims to take advantage of predator avoidance behaviour by herding fish into the path of the oncoming net (Ryer and Barnett, 2006; Winger et al., 2010a). Blaxter et al. (1964) observed that when fish come in contact with a trawl, their response - both in a laboratory and at sea - is highly affected by the quantity of light available.

Of the factors affecting fish behaviour in response to an approaching bottom trawl, visual stimuli are the most important (Blaxter et al., 1964; Glass and Wardle, 1989; Walsh, 1991; Ryer and Barnett, 2006; Arimoto et al., 2010; Winger et al., 2010a). Glass and Wardle (1989) found that vision influenced herding behaviour more than any other sense. Ryer and Barnett (2006) observed that fish, particularly flatfish, display disordered actions when confronted with a trawl in low light conditions, leading to larger catches. This theory is supported by at-sea studies which have found nighttime catch rates to be greater than daytime catch rates for multiple species of fish including yellowtail flounder (*Limanda ferruginea*) (Walsh, 1991; Casey and Myers, 1998; Petrakis et al., 2001).

In this research I hypothesized that low ambient light conditions (i.e. nighttime and seasons with fewer and darker daylight hours) lead to higher catch rates in commercial tows of yellowtail flounder on the Grand Bank, Newfoundland and Labrador, Canada. Data coverage in previous studies has been limited temporally because research cruises only operate for relatively short time periods. By using industry logbooks, which have a broad temporal scale due to the nearly year-round operation of vessels, I investigated the diel and seasonal patterns of catch rate (kg/min) to determine the effect of ambient light on gear and yellowtail flounder interactions.

2.2 Materials and Methods

Statistical analysis was completed on catch rate data from two vessels: the *F/V Mersey Viking* and the *F/V Aqviq* (henceforth referred to as the *Viking* and *Aqviq*, respectively). Both vessels were equipped with Goldentop bottom trawls, Thyboron trawl doors, and rock hopper footgear. During the study period the codend mesh size for both vessels ranged from 145-152 mm, the headline length was 31m, and Suzuki sounders were used (for more information please see Winger et al., 2010b). The *Viking* completed tows in every month of 2008 (Table 2.1), however, in that year, the *Aqviq* only completed tows from January to September (Table 2.2). In order to have a complete dataset for the *Aqviq*, tows from October to December 2009 were incorporated. We recognize that this may introduce bias as the conditions during 2009 may have been different from 2008, however, the benefits of analyzing a complete year outweigh the impacts of combining data. Seasons were defined as follows, winter: January, February; spring: March, April, May; summer: June, July, August, September; fall: October, November, December. The fishery was conducted on the Grand Bank of Newfoundland in NAFO Divisions 3LNO at water depths ranging from 40 to 83 m (Fig. 2.1 and 2.2). Tows occurred at all times of the day and night; however, in order to strictly compare day tows to night tows all trips were divided into three periods: day, night, and twilight.

Twilight was defined as any tow starting in the period between one hour before civil twilight starts (when the center of the sun is 6 degrees below the horizon) and actual sunrise. At the end of the day, twilight is defined as a tow starting in the period between one hour before sunset and the end of civil twilight (when the center of the sun is again 6 degrees below the horizon). In this way, tows occurring during dawn and dusk - and thus receiving an indeterminate amount of sunlight - could be disregarded. Catch rates were calculated as total catch (kg) divided by tow duration (minutes).

A Two-Way ANOVA was used to detect effects of season and time of day (i.e., day or night) and their combined interaction effects on catch rate (kg/min). Data distributions were checked and deemed normal prior to proceeding with analysis. A Tukey's honestly significant difference test was then used to conduct post hoc comparisons of catch rate. A Bonferroni correction was applied as part of the Tukey's HSD test to the probability level to reduce the family-wise type I error rate (α 0.05 divided by the number of tests (n=6); giving $p<0.008$). One-way ANOVAs were used to determine whether daytime and nighttime catch rates were different between seasons. A Tamhane's post hoc test was used, and a Bonferroni correction was applied to the probability level to reduce the family-wise type I error rate (α 0.05 divided by the number of tests (n=6); giving $p<0.008$). Independent t-tests were used to determine whether catch rates varied among time periods in each season. Separate tests were conducted on the *Viking* and *Aqviq* in order to control for differences in gear modifications and harvesting strategies between the vessel captains. All statistical tests were performed using IBM SPSS Statistics 19.

2.3 Results

In 2008, the *Viking* completed 1224 tows excluding those that occurred in twilight (winter [n=241]; spring [n=353]; summer [n=330]; fall [n=300]). Of these, 668 occurred during the day and 556 occurred during the night. Catch rates for individual tows ranged from 0.00 to 62.25 kg/min. Mean seasonal rates ranged from 8.86 kg/min in spring to 16.55 kg/min in summer. The mean daytime catch rate for all seasons combined was 12.76 kg/min which fell within a range from 9.02 kg/min in spring to 16.50 kg/min in summer. The mean nighttime catch rate for all seasons combined was 13.68 kg/min which fell within a range between 8.64 kg/min in spring and 16.67 kg/min in summer (Table 2.3).

A two-way analysis of variance test revealed significant effects of both time of day and season on *Viking* catch rate ($F_{[1,1216]} = 6.97$; $p = 0.008$ and $F_{[3,1216]} = 102.05$; $p < 0.001$, respectively), as well as their interaction ($F_{[3,1216]} = 3.41$; $p = 0.017$). Tukey's honestly significant difference post hoc test with a Bonferroni correction (α 0.05/6 = 0.008) revealed that catch rate was significantly different between all seasons except for winter and summer (Table 2.4).

When comparing daytime catch rates, a one-way analysis of variance test revealed significant differences between seasons ($F_{[3,664]} = 81.93$; $p < 0.001$). Tamhane's post hoc test with a Bonferroni correction (α 0.05/6 = 0.008) found that daytime catch rate was significantly different between winter and spring, spring and summer, spring and fall, and summer and fall, but this difference could not be detected between winter and summer, and winter and fall (Table 2.5). When comparing daytime catch rates between seasons, catch rates were significantly higher in summer and winter compared to spring or fall. Fall daytime catch rates were significantly lower than summer, but significantly higher than spring. During spring, the daytime catch rates were significantly lower than all other seasons (Fig. 2.3).

When comparing nighttime catch rates, a one-way analysis of variance test revealed significant differences between seasons ($F_{[3,552]} = 34.78$; $p < 0.001$). Tamhane's post hoc test with a Bonferroni correction (α 0.05/6 = 0.008) revealed that nighttime catch rate was significantly different between winter and spring, spring and summer, spring and fall, and summer and fall (Table 2.5). When comparing nighttime catch rates between seasons, catch rates were significantly higher in summer than in spring or fall. During winter, nighttime catch rates were significantly higher than during spring. Fall nighttime catch rates were significantly higher than spring, and significantly lower than those during summer. Lastly, nighttime catch rates were significantly lower in spring than in any other season (Fig. 2.4).

T-tests examining differences between day and night for each season on the *Viking* revealed that the only season with significant differences between daytime and nighttime catch rates was fall, where night rates were significantly higher than day rates ($p = 0.002$) (Fig. 2.5). Winter and summer mean nighttime catch rates were also higher than daytime though they were not statistically significant.

For the *Aqviq*, 1612 tows were included in this study (winter [n=257]; spring [n=388]; summer [n=598]; fall [n=369]), of which 878 occurred during the day and 734 at night. Catch rates for individual tows ranged from 0.00 to 52.55 kg/min. Mean seasonal rates ranged from 12.13 kg/min in fall to 18.49 kg/min in summer. The mean daytime catch rate for all seasons combined was 14.45 kg/min, ranging from 11.19 kg/min in fall to 18.02 kg/min in summer. The mean nighttime catch rate for all seasons combined was 15.69 kg/min, ranging from 12.38 kg/min in spring to 19.32 kg/min in summer (Table 2.6).

A two-way analysis of variance test showed significant effects of time of day and season on catch rate ($F_{[1,1604]} = 11.05$; $p = 0.001$ and $F_{[3,1604]} = 96.97$; $p < 0.001$, respectively). Unlike the *Viking*, the interaction term was non-significant ($F_{[3,1604]} = 1.35$; $p = 0.256$) (Table 2.7). Tukey's post hoc test with a Bonferroni correction (α 0.05/6 = 0.008) revealed that catch rate was significantly different between all seasons except for winter and summer, and spring and fall.

A one-way analysis of variance test comparing daytime catch rates revealed significant differences between seasons ($F_{[3,874]} = 63.19$; $p < 0.001$). Tamhane's post hoc comparisons tests with a Bonferroni correction (α 0.05/6 = 0.008) revealed that daytime catch rate was significantly different between winter and spring, winter and fall, spring and summer, and summer and fall, but this difference could not be detected between winter and summer, and spring and fall (Table 2.8). When comparing daytime catch rate between seasons, rates were significantly higher in summer and winter compared to spring or fall (Fig. 2.6).

When comparing nighttime catch rates, a one-way analysis of variance test revealed significant differences between seasons ($F_{[3,730]} = 40.35$; $p < 0.001$). Tamhane's post hoc comparison tests with a Bonferroni correction (α 0.05/6 = 0.008) revealed that nighttime catch rate was significantly different between winter and spring, winter and fall, spring and summer, and summer and fall. Significant differences were not found when comparing winter and summer and spring and fall (Table 2.8). When comparing nighttime catch rates between seasons, catch rates were significantly higher in summer and winter than in spring or fall (Fig. 2.7).

T-tests were used to analyze differences between mean night and day catch rates for the *Aqviq*. These results showed that only summer and fall have significant differences between night and day catch rates; night rates are significantly higher than day rates for both seasons ($p = 0.026$ and $p = 0.025$, respectively). Winter mean nighttime catch rates are also higher than day rates, though they are not statistically significant (Fig. 2.8).

2.4 Discussion

The results of the analysis revealed that season had a statistically significant effect on mean catch rate for two Ocean Choice International (OCI) vessels fishing yellowtail flounder on the Grand Bank in 2008 – 2009. The results of the seasonal trend analysis showed higher catch rates occurring in summer and winter for both vessels which is different from the original hypothesis that stated only seasons with fewer, darker daylight hours would have the highest catch rates. Our findings are consistent with Walsh and Brodie (2006) who found commercial yellowtail catch per unit effort (CPUE) highest in January and June; our results are also consistent with Maddock Parsons et al. (2005) who found catch rate lowest in March. However, opposite from our results, Walsh and Brodie (2006) also found April to have a relatively high CPUE. Why do these patterns of high/low catch rates change between years?

When investigating these temporal patterns it is important to note that yellowtail flounder generally do not migrate or aggregate to feed and spawn (Walsh and Morgan, 2004). Therefore we may reason that the observed high catch rates in our study period are not due to fish forming large assemblages, but instead may be due to seasonal variation in local environmental patterns. During winter 2008, mean temperature near the seafloor was around 3°C, the warmest seasonal average for that year (see Chapter 3 for review of environmental data). Higher water temperature enhances swimming capability and endurance, enabling flatfish in the sweep zone -the area between the trawl wings and door- to enter the path of an oncoming bottom trawl for subsequent capture (Winger et al., 1999). Trawls are designed to take advantage of fish avoidance behaviour by herding them to a center point and minimizing escapes (Ryer, 2008). We speculate that the high catch rates observed in winter in this study are the result of increased water temperatures near the seafloor, increasing the herding capability of yellowtail flounder, and as a result, increasing the volume of fish arriving in the net mouth which become vulnerable to capture. This would be consistent with the temperature-dependent herding of flatfish predicted by Winger et al. (1999) using laboratory observations.

Environmental conditions may also be the cause for high catch rates in summer. During summer 2008, mean wind speeds on the Grand Bank were about 6 m/sec, the lowest seasonal average for that year (see Chapter 3 for review of environmental data). Vessel motion due to high wind speed impacts trawl efficiency through alteration of trawl geometry and contact with the seabed (Stewart et al., 2010; Politis et al., 2012). Towing parallel to wind and wave direction can somewhat mitigate vessel response to sea state, however, past research shows that catch rates decrease as wave heights increase (Stewart et al., 2010). We speculate that high catch rates observed in summer are the result of low wind speeds, which would otherwise alter trawl performance and decrease catch rate. The importance of seasonally varying factors will be explored further in the next chapter.

The results of the analysis also revealed that time of day had a statistically significant effect on catch rate for both vessels in some seasons. In general, daytime and nighttime catches were highest in summer and lowest in spring. Winter had the second highest catch rates. These patterns were observed for both vessels. Although not always statistically significant, we found mean night catch rates to be higher than day catch rates in all seasons except for spring. Previous research supports these findings; during nighttime, low light levels and nocturnal movements off of the sea floor may cause yellowtail flounder to become more vulnerable to trawl capture (Walsh, 1988). Laboratory tests conducted on flatfish by Ryer and Barnett (2006) found when flatfish are confronted with trawl components at night there were more startle responses and less herding. Additionally, Walsh and Morgan (2004) found that yellowtail flounder rise off the sea floor at night. The findings from our study suggest that the absence of visual stimulus at night may lead to unordered interactions between fish and trawls; we speculate that this may result in higher catches. Also, rising off of the seafloor may make yellowtail flounder more available to trawls by putting them into the direct path of the gear.

Overall, there was a noticeable difference of seasonal catch rates between vessels. This may be attributed to the auto-trawl system on the *Aqviq*, a device on the winch that maintains trawl geometry even in windy and stormy conditions (G. Thorbjornsson, personal communication, March 8, 2012). Gear technology is a crucial factor in trawl efficiency, and as such we did not perform in-depth analysis between the *Aqviq* and the *Viking*.

2.4.1 Limitations to Approach

It is important to note the limitations in this study. The use of a single year's worth of data warrants caution when interpreting and applying results. Future projects would benefit from a longer, uninterrupted study period and the inclusion of environmental data in analysis. It should also be mentioned that commercial catch rates are influenced by more than just fish availability: operational variation due to crew experience or gear attributes, and avoidance of bycatch, undersize, and poor quality fish all impact catch and effort. Market conditions determining retail price and demand for product are also important factors influencing catch.

2.5 Conclusion

In conclusion, we found that commercial catch rates of yellowtail flounder were influenced by time of day and season. We speculate that high nighttime catch rates are attributed to reduced ambient light intensity near the seafloor and a concomitant reduction in avoidance capability, leading to increased vulnerability to capture. High catch rates during winter with relatively warm water temperatures are attributed to increased herding, owing to the fact that warmer water temperatures are known to enhance swimming speed and endurance, both of which are necessary for flatfish to reach the trawl path. High catch rates during summer are attributed to enhanced trawl performance due to low wind speeds which, in other seasons, may alter trawl geometry and contact with the seabed. The results from this research quantified and confirmed temporal patterns in this fishery. It is recommended that fewer fishing trips be made in spring, and more effort put into winter and summer trips. I also recommend future multiyear analysis and further research on diurnal patterns in order to verify these findings and enhance industry practices.

Table 2.1: Mean monthly catch rate (kg/min) from the *Viking*. SD = Standard deviation.

	2008	
Month	**Mean**	**SD**
January	13.72	7.77
February	16.18	7.80
March	8.06	5.32
April	7.21	3.44
May	10.93	4.45
June	17.20	4.72
July	17.44	4.53
August	15.39	4.11
September	19.75	6.41
October	9.98	4.13
November	15.27	6.93
December	13.18	7.39

Table 2.2: Mean monthly catch rate (kg/min) from the *Aqviq*. SD = Standard deviation.

	2008	
Month	**Mean**	**SD**
January	15.90	9.52
February	19.19	9.53
March	9.67	5.70
April	10.84	4.48
May	15.59	5.68
June	19.28	4.17
July	21.32	5.28
August	18.34	7.27
September	15.57	6.80
	2009	
October	13.81	7.43
November	13.43	5.65
December	7.23	4.70

Table 2.3: Mean seasonal catch rate (kg/min) caught by the *Viking*. SD = Standard deviation.

			Day		Night	
Season	**Tows (N)**	**Mean**	**Mean**	**SD**	**Mean**	**SD**
Winter	241	15.08	14.15	7.04	15.72	8.52
Spring	353	8.87	9.02	4.31	8.64	4.88
Summer	330	16.55	16.50	4.42	16.67	5.00
Fall	300	12.64	11.35	5.90	13.67	6.86

Table 2.4: Two-way analysis of variance for the effect of season, time of day, and their interaction on *Viking* catch rates. Tukey's HSD post hoc seasonal comparisons (winter: W; spring: Sp; summer: S; fall: F). Significant values shown in bold.

						Tukey's HSD post hoc			
Source	**SS**	**df**	**MS**	**F**	**P**	**Season**	**Sp**	**S**	**F**
Time	239.30	1	239.30	6.97	**0.008**	W	**.000**	.016	**.000**
Season	10514.28	3	3504.76	102.05	**<0.0001**	Sp		**.000**	**.000**
Interaction	351.32	3	117.11	3.41	**0.017**	S			**.000**
Error	41762.92	1216	34.35						
Total	263295.12	1224							

Table 2.5: One-way analysis of variance for the effect of season on daytime and nighttime *Viking* catch rates. Tamhane's post-hoc seasonal comparisons (winter: W; spring: Sp; summer: S; fall: F). Significant values shown in bold.

Time							Tamhane's post hoc			
of Day	**Source**	**SS**	**df**	**MS**	**F**	**P**	**Season**	**Sp**	**S**	**F**
Day	Between Seasons	6553.28	3	2184.43	81.93	**.000**	W	**.000**	.017	.010
	Within Seasons	17702.70	664	26.66			Sp		**.000**	**.001**
	Total	24255.98	667				S			**.000**
Night	Between Seasons	4634.71	3	1544.90	34.78	**.000**	W	**.000**	.662	.214
	Within Seasons	24516.79	552	44.41			Sp		**.000**	**.000**
	Total	29151.50	555				S			**.000**

Table 2.6: Mean seasonal catch rate (kg/min) caught by the *Aqviq*. SD = Standard deviation.

			Day		Night	
Season	**Tows (N)**	**Mean**	**Mean**	**SD**	**Mean**	**SD**
Winter	257	17.41	16.18	8.68	18.26	10.20
Spring	388	12.39	12.40	5.55	12.38	6.42
Summer	598	18.49	18.02	5.91	19.32	7.33
Fall	369	12.13	11.19	6.20	12.78	7.04

Table 2.7: Two-way analysis of variance for the effect of season, time of day, and their interaction on *Aqviq* catch rates. Tukey's HSD post hoc seasonal comparisons (winter: W; spring: Sp; summer: S; fall: F). Significant values shown in bold.

						Tukey's HSD post hoc			
Source	**SS**	**df**	**MS**	**F**	**P**	**Season**	**Sp**	**S**	**F**
Time	539.74	1	539.74	11.05	**0.001**	W	**.000**	.161	**.000**
Season	14212.90	3	4737.63	96.97	**0.000**	Sp		**.000**	.954
Interaction	198.29	3	66.10	1.35	0.256	S			**.000**
Error	78363.35	1604	48.86						
Total	475371.92	1612							

Table 2.8: One-way analysis of variance for the effect of season on daytime and nighttime *Aqviq* catch rates. Tamhane's post-hoc seasonal comparisons (winter: W; spring: Sp; summer: S; fall: F). Significant values shown in bold.

							Tamhane Post-hoc Comparison			
Data Set	**Source**	**SS**	**df**	**MS**	**F**	**P**	**Season**	**Sp**	**S**	**F**
Day	Between Seasons	7434.55	3	2478.18	63.19	**.000**	W	**.000**	.233	**.000**
	Within Seasons	34274.57	874	39.22			Sp		**.000**	.269
	Total	41709.11	877				S			**.000**
Night	Between Seasons	7310.59	3	2436.86	40.35	**.000**	W	**.000**	.853	**.000**
	Within Seasons	44088.78	730	60.40			Sp		**.000**	.994
	Total	51399.37	733				S			**.000**

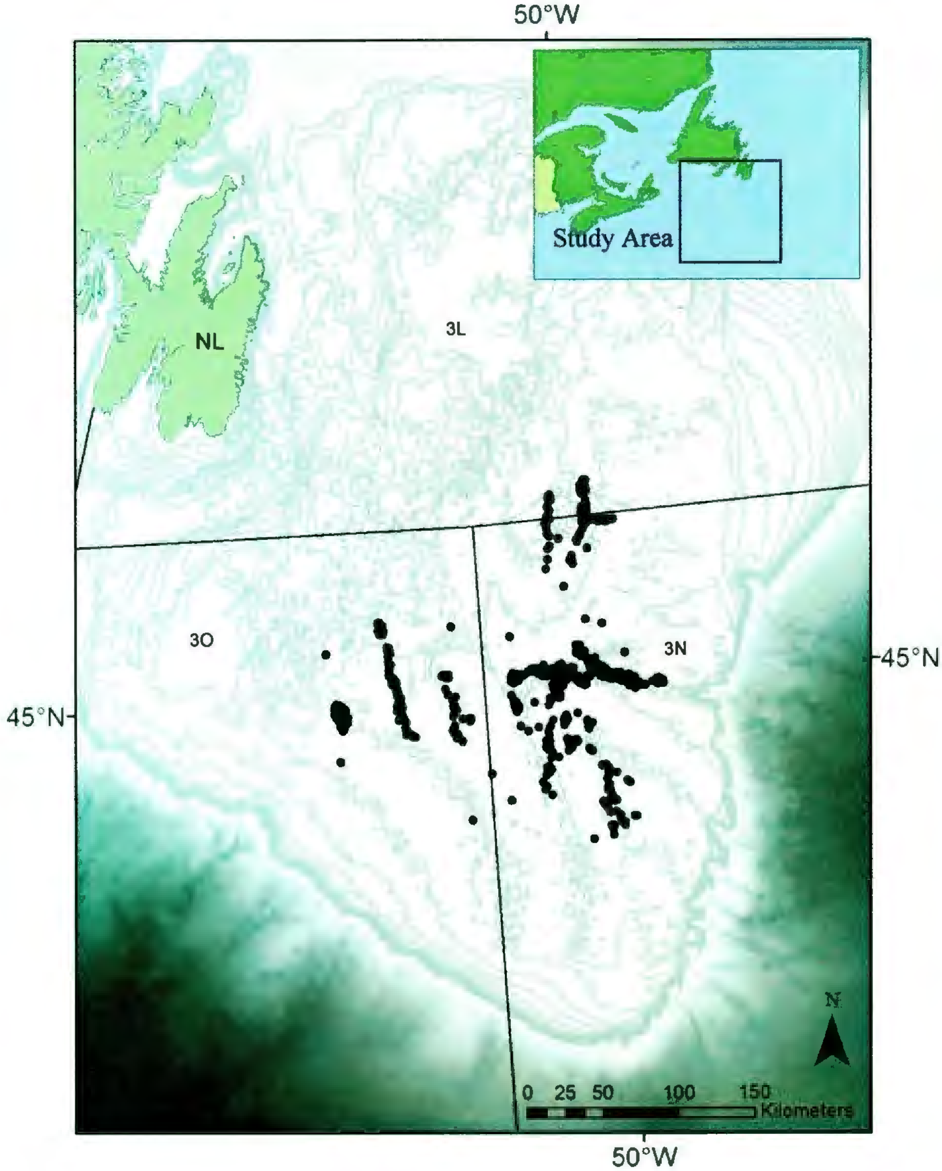

Figure 2.1: Map of Newfoundland (insert), showing the study area location in the Atlantic Ocean. Locations of *Viking* tows are distributed between NAFO Divisions 3LNO.

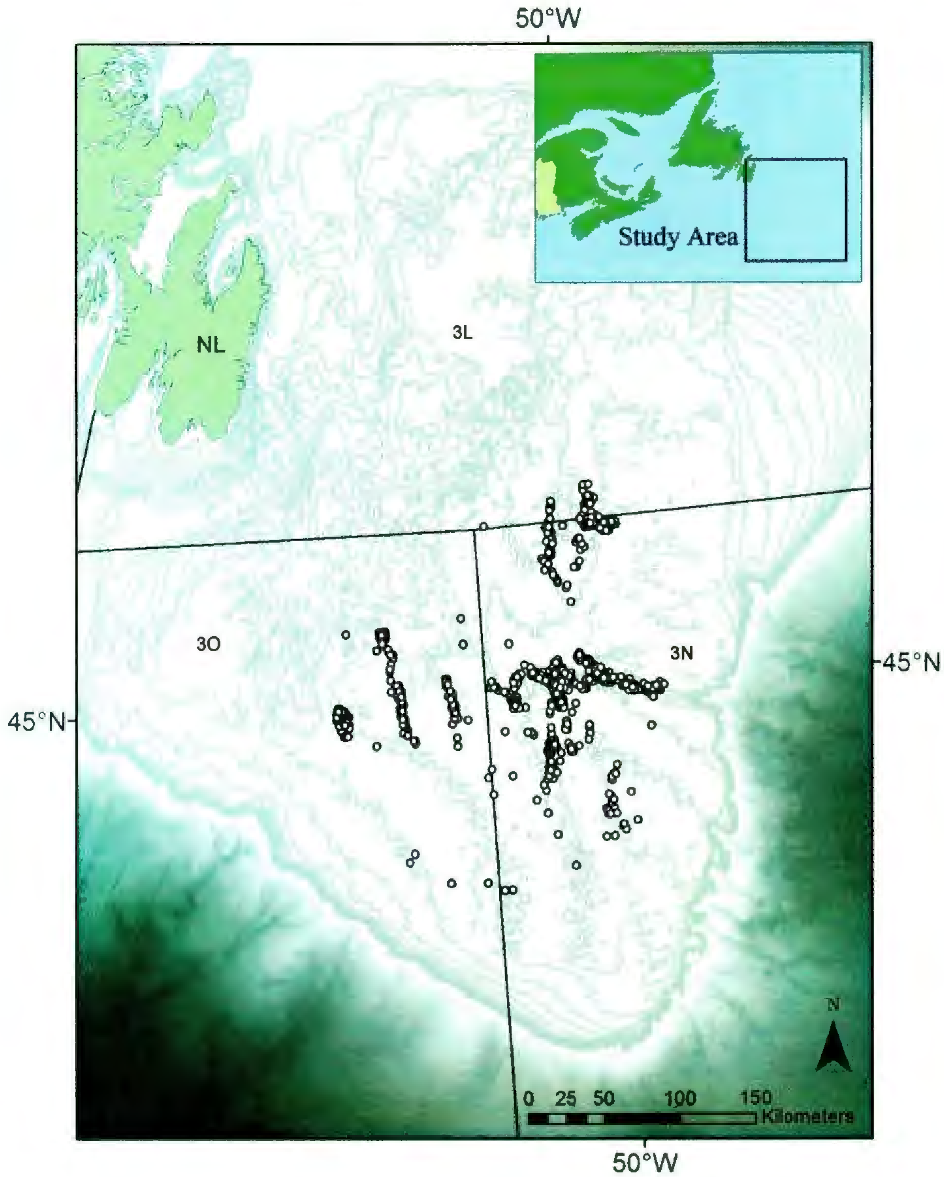

Figure 2.2: Map of Newfoundland (insert), showing the study area location in the Atlantic Ocean. Locations of *Aqviq* tows are distributed between NAFO Divisions 3LNO.

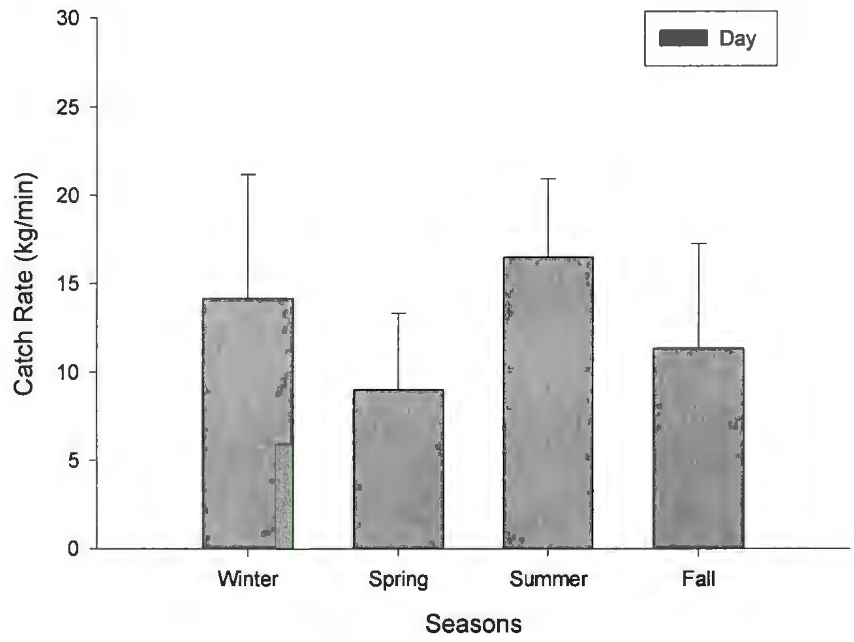

Figure 2.3: Mean daytime catch rate (kg/min) for the *Viking* by season with standard deviation bars.

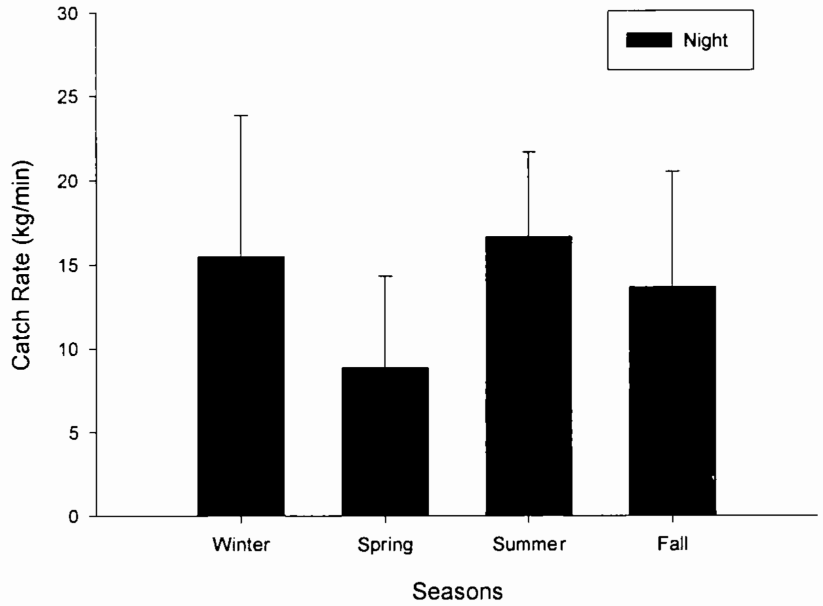

Figure 2.4: mean nighttime catch rate (kg/min) for the *Viking* by season with standard deviation bars.

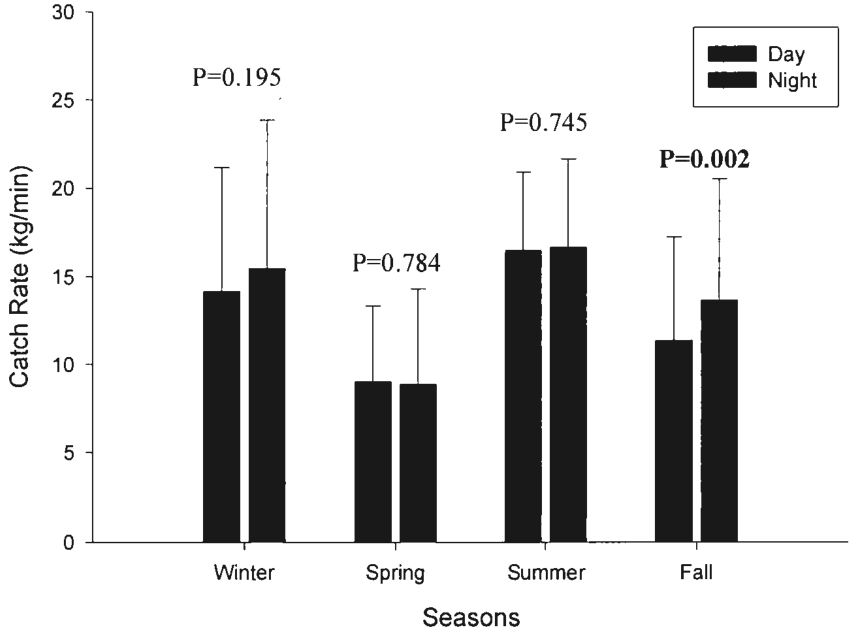

Figure 2.5: Mean daytime and night catch rate (kg/min) per season with standard deviation for the *Viking*. Fall has a significant difference (shown in bold) between daytime and nighttime mean catch rates.

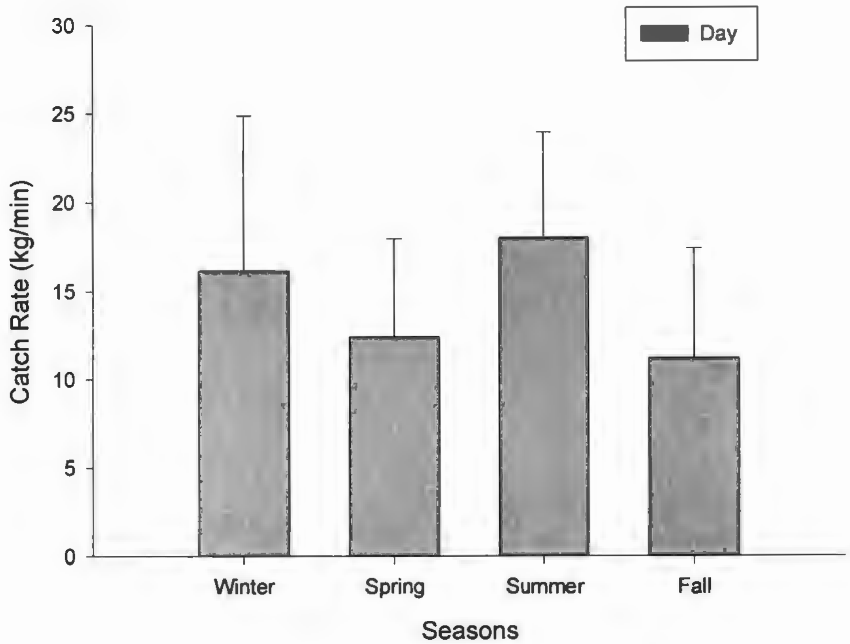

Figure 2.6: Mean daytime catch rate (kg/min) for the *Aqviq* by season with standard deviation bars.

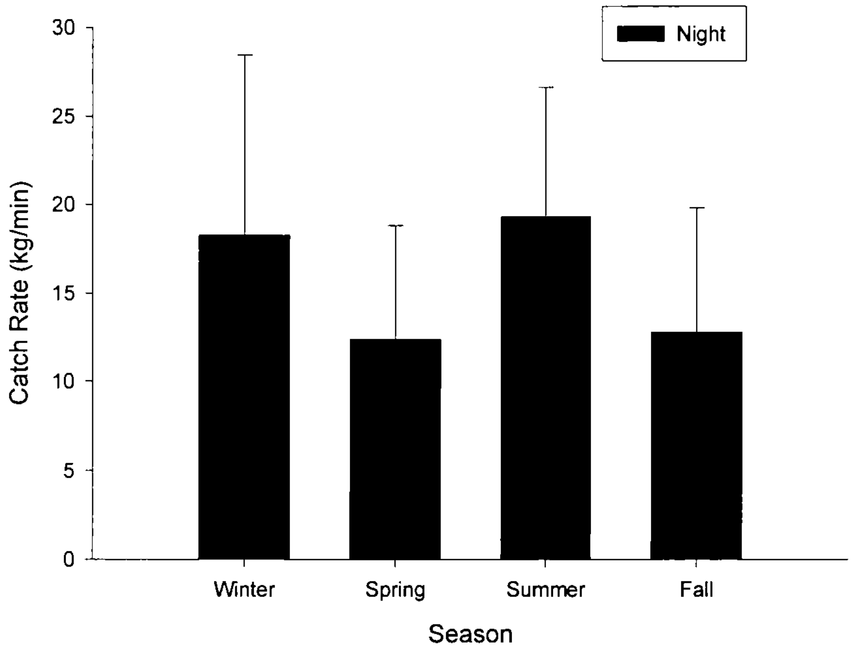

Figure 2.7: Mean nighttime catch rate (kg/min) for the *Aqviq* by season with standard deviation bars.

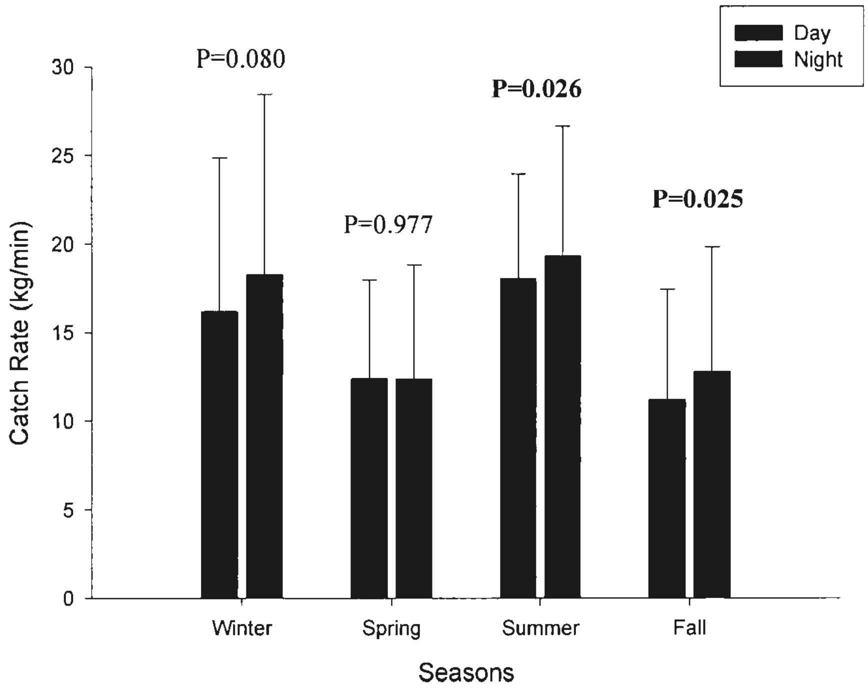

Figure 2.8: Mean daytime and nighttime catch rate (kg/min) per season with standard deviation for the *Aqviq*. Summer and fall have significant differences (shown in bold) between daytime and nighttime mean catch rates.

Chapter 3: Environmental impact on commercial catch rate of yellowtail flounder (*Limanda ferruginea*) on the Grand Bank of Newfoundland

Abstract

Wind speed, water depth, sediment type, and bottom water temperature were related to commercial catch rate of yellowtail flounder (*Limanda ferruginea*) from the *F/V Mersey Viking* (1405 tows) and *F/V Aqviq* (1563 tows) on the Grand Bank, Newfoundland and Labrador, Canada. Relationships were examined using Geographically Weighted Regressions (GWR) and linear regressions. High catch rates were related to low wind speeds, deep fishing depths in spring and summer, shallow fishing depths in fall, fine-grained sediment type, and warm bottom water temperatures in the winter. Sediment type was the least statistically significant variable. Bottom water temperature had mixed negative and positive relationships in spring, summer, and fall. GWR was an improvement over classical statistical methods as evidenced by lower Akaike Information Criterion (AIC_c) values and higher r^2 values.

3.1 Introduction

Interactions between fish and their habitat have been known about since time immemorial (Rose, 2005). This knowledge shifted from anecdotal to systematic studies with the creation of fisheries oceanography, and it was found that environment could impact fish growth, recruitment, and behaviour (Frank et al., 1990; Helbig et al., 1992;

Lehodey et al., 2006; Winger et al., 2010a). With increasing evidence that our climate is changing it is even more important to understand the connections between climate, the physical environment, and fish species. The effects of habitat on commercial fisheries has been studied before in the Pacific Ocean (Perry et al., 2000), North Sea (Wieland et al., 2009), Lake Winnipeg (Speers, 2006), and Atlantic Ocean (Walsh and Brodie, 2006). However, these studies are often done using data averages applied to whole study areas, resulting in a global model which masks local heterogeneity (Windle et al., 2009). The acceptance of spatial non-stationarity (i.e. relationships between variables that are not constant over large spatial ranges) in statistical modeling allows us to investigate relationships between commercial catch rate and environmental variables on a variety of scales, including local.

In Newfoundland, commercial fisheries on the Grand Bank have been studied in relation to their environment. The yellowtail flounder (*Limanda ferruginea*) is one such species that has received much interest due to its economic value, recent stock collapse, and subsequent recovery (Brodie et al., 2010). It is known to inhabit waters from 3.0° C to 5.0° C and live at water depths of 35 to 85 meters; water depth is more limiting to the distribution of this species than bottom temperature (Bowering and Brodie, 1991; Murawski, 1993). The sand, shell, and gravel substrates of the Grand Bank provide ideal foraging habitat and safety for juvenile and adult yellowtail flounder (Walsh, 1992; Simpson and Walsh, 2004).

In this research, I hypothesized that:

1) catch rate will increase with decreasing wind speed,
2) catch rate will increase with deepening water depths,
3) catch rate will increase with decreasing sediment size, and
4) catch rate will increase with increasing bottom water temperatures.

These variables were included because of their roles in fish distribution and their impact on captains' decision making processes, both of which directly and indirectly influence catch rate. Until recently, the analysis of these relationships would be limited to global regression models which average values over large areas. However, recent studies using local regression methods such as Geographically Weighted Regression (GWR) have shown that the relationships between catch rates and environmental variables are likely to be non-stationary (Windle et al., 2009). Given these findings, I investigated the relationships between yellowtail flounder commercial catch rate and wind speed, water depth, sediment type, and bottom water temperature using GWR.

3.1.1 Geographically Weighted Regression

A major issue facing scientists is the need to perform statistical analysis with spatially varying relationships and processes. Non-stationarity exists when relationships change over space, a common occurrence in ecological studies of such things as tree growth patterns, density of animals, and the distribution of wildlife (Zhang and Shi, 2004; Shi et al., 2006; Osborne et al., 2007). Classical statistics are incapable of producing reliable analyses when non-stationarity and spatial autocorrelation, or dependence between data points, is present (Legendre and Fortin, 1989). Additionally, classical statistics tend to generalize relationships over global areas, thus smoothing local variation. We can address both non-stationarity and local issues using spatial statistical tools. GWR is a relatively new technique used to incorporate local spatial variation into statistical analyses by modifying regression models to produce local parameter estimates for each set of relationships (Fotheringham et al., 2002; Charlton et al., 2006). Each point in a study area is influenced by its surrounding observed data which is weighted more than points located farther away (Charlton et al., 2006).

A global regression equation takes the form:

$$y_i = \beta_o + \sum_k \beta_k X_{ik} + \varepsilon_i \qquad (1)$$

Where y_i is the response variable, β_o is the intercept coefficient, β_k is the coefficient for the explanatory variable ($k = 1,2,3, \ldots, n$), X_{ik} is a matrix of the predictor variables ($i = 1,2,3, \ldots, n$; $k = 1,2,3, \ldots, p$) and ε_i is the random error term in the model. In GWR, geographic coordinates of the *i*th point are incorporated as follows:

$$y_i = \beta_o(u_i, v_i) + \sum_k \beta_k (u_i, v_i) X_{ik} + \varepsilon_i \qquad (2)$$

Where (u_i, v_i) represents the coordinates at point *i*. GWR uses a weighted least squares regression model to weight different coefficients (Brunsdon et al., 1996):

$$\beta_o(u_i, v_i) = (X^T W(u_i,v_i) X)^{-1} X^T W(u_i,v_i) Y \qquad (3)$$

Weights, or kernels, are determined using exponential distance decay functions with varying bandwidths to delimit proximal neighbourhoods. To determine bandwidth value, the Akaike Information Criterion (AIC_c) minimization can be used. Bandwidths can be adaptive (i.e., varied over space depending on point density) or constant (i.e., constant over space regardless of point density). For more information on GWR please see Fotheringham et al. (2002).

3.2 Materials and Methods

Global and local regression analyses were used to investigate the relationship between commercial catch rate of yellowtail flounder and the following environmental variables: wind speed, water depth, substrate type, and bottom water temperature. Catch rates were taken from the commercial logbooks of the *F/V Mersey Viking* and the *F/V Aqviq* (henceforth referred to as the *Viking* and *Aqviq,* respectively) for the fishing seasons of 2007 – 2009, however, due to incomplete data, only logbooks from 2008 were used in analysis. These vessels are owned and operated by Ocean Choice International (OCI). Both vessels were equipped with Goldentop bottom trawls, Thyboron trawl doors, and rock hopper footgear. During the study period the codend mesh size for both vessels ranged from 145-152 mm, the headline length was 31m, and Suzuki sounders were used (for more information please see Winger et al., 2010b). Each vessel dataset was divided into subsets by season (winter: December of previous year, January, February; spring: March, April, May; summer: June, July, August; fall: September, October, November). Tows took place on the Grand Bank, off Newfoundland, in NAFO Divisions 3LNO (Fig. 3.1 and 3.2). Digitized industry logbooks were obtained from the Department of Fisheries and Oceans (DFO). These documents provided total catch of legal size yellowtail flounder (>300g; NAFO minimum legal size 28cm; round kg), tow duration (minutes), and the location of the vessel at tow start (latitude and longitude).

Catch rate (kg/min) was chosen as the dependent variable. The two vessels were examined individually to control for differences in captains' harvesting styles; though both captains have similar levels of experience fishing yellowtail flounder for OCI, their fishing strategies may be different.

The analysis used environmental data collected from multiple sources, and as such, data manipulation was required. Wind speed was determined using a DFO hind cast dataset, MSC50, which used climate models and historical meteorological records to simulate surface winds and ocean waves. These predictions were validated *in situ* with Canadian and international buoys and measurement platforms; they were also compared with weather ship and satellite data to ensure accuracy (Swail et al., 2006). The resulting grid points are 30 nautical miles apart and contain hourly hindcasted wind and wave conditions. In order to match irregularly spaced tow locations with these gridded data, a computer programmer at the Marine Institute was enlisted to write SQL script which would link tow locations to the nearest grid point in space and time. To decrease processing time, wind speeds were averaged over 6-hour time periods, and tow locations were linked to these averages.

Water depths from logbooks were deemed to be inaccurate. Inconsistent units, imprecise rounding, and differences between recorded depths and oceanic charts led to a search for more accurate data from the Canadian Hydrographic Services (CHS). The Northwest Atlantic database is a regional compilation of bathymetric data points from different sources which have been carefully checked for accuracy, precision and error (Varma et al., 2008). These data points were interpolated using the inverse distance weighted (IDW) technique in the Spatial Analyst toolbox in ArcGIS 10. IDW, a commonly used technique, was chosen as it minimizes the root mean square error (RMSE), works well in dense data sets, and gives more weight to proximal data points. As the Grand Bank is relatively flat and unchanging, this interpolation method was deemed the most appropriate. The output raster cell size was 0.0083 decimal degrees, the exponent of distance (p value) was 2 (as p increased distant points were given less weight), and the search radius was 12 points.

Substrate type was obtained from DFO ROXANN data which have been previously used in habitat studies of yellowtail flounder (Simpson and Walsh, 2004) and cold water crab species (Mullowney et al., 2012). Data were opportunistically collected year-round between 1994 and 2005 aboard the *CCGS Templemen* using a Simrad EK500 echosounder placed on the middle of the hull, with data collection intervals of 4 seconds. Data points consisted of sediment signatures at locations along survey tracks, on which ordinary kriging methods were performed to interpolate a surface. Neither transformations nor trend removals were performed, and a Stable semivariogram model type was used. The lag size was 0.012 decimal degrees, and there were 12 lags. All specifications were done in order to minimize the RMSE. Using this estimated surface of sediment classification, interpolated substrate type was extracted at each tow location.

Monthly average bottom water temperatures were obtained from Integrated Science and Data Management, a service run by DFO, who maintain an open access archival hydrographic database. The data were gathered by Canadian and international sources using various methods: hydrographic bottles, CTD casts, profiling tows, Batfish tows, and bathythermographs. Data points containing latitude, longitude, and average bottom temperature were grouped into the same seasons as catch rate and then mapped in ArcGIS 10. The spatial analyst technique IDW was used to interpolate smooth surfaces for each season. While there were fewer data points in this data set as compared to wind speed, IDW was determined to be the most appropriate test given that it minimized RMSE and predicted values using proximal temperatures. The output raster cell size for each seasonal surface was 0.016 decimal degrees, the exponent of distance (p) was 2, and the search radius was 12 points. Lastly, interpolated values of water temperatures near the seafloor were extracted at each tow location.

After the manipulation of data, a linear regression and GWR were performed on catch rate and the environmental variables. The linear regression was conducted using IBM SPSS Statistics 19 and the GWR was conducted using GWR 3.0 software (available at http://ncg.nuim.ie/ncg/GWR/). Variance Inflation Factors (VIF), or correlation values among multiple variables, were reported with the linear regression results. GWR weights were assigned following a Gaussian curve, and optimal bandwidths were chosen using AIC_c. An adaptive kernel was used, allowing kernel size to change with density of points. Local and global models were compared by their AIC_c value and r^2 values in order to determine whether the local GWR models were an improvement over the global linear regression models. Residuals, the model error that is the difference between the observed and predicted variable value, were analyzed for spatial autocorrelation using the global Moran's I tool in ArcGIS Spatial Statistics toolbox. Lastly, a Monte Carlo significance test was run for each GWR model which indicated if there was significant spatial non-stationarity in each local parameter estimate (Charlton et al., 2006). GWR results, the model parameter coefficients, and model fit (r^2) were mapped and compared visually in ArcGIS 10.

3.3 Results

3.3.1 *Viking*

A wide range of environmental conditions existed in NAFO Divisions 3LNO during the 2008 *Viking* fishing season (Fig. 3.3). In winter, average hourly wind speeds ranged from 1.7 to 19.4 m/s (mean ± SD; 9.5m/s ± 3.7m/s), depth of catch ranged from 40 to 70 m (57.1m ± 4.3m), and bottom water temperatures were between 1.9 and 3.5°C (2.8°C ± 0.3°C). In spring, wind speeds ranged from 1.7 to 18.4 m/s (7.9m/s ± 3.4m/s), water depths ranged from 42 to 78 m (61.8m ± 5.8m), and bottom water temperatures were between 0.3 and 3.8°C (1.8°C ± 0.9°C). In summer, wind speeds ranged from 1.0 to 10.6 m/s (5.5m/s ± 2.1m/s), water depths were the deepest, ranging from 53 to 83m (68.3m ± 8.2m), and bottom water temperatures were the coldest, varying between -0.1 and 2.7°C (1.3° C± 0.6°C). In fall, wind speeds varied from 1.7 to 15.3 m/s (7.8m/s ± 3.0m/s), water depths ranged from 51 to 83 m (62.1m ± 7.2m), and bottom water temperatures were the warmest, ranging between 0.1 and 4.9°C (1.9°C ± 0.6°C). For all four seasons, yellowtail flounder were mostly caught in areas classified as gravel substrate based on ROXANN acoustic surveys. Mean catch rates were highest in summer (16.50 kg/min; range: 5.5 – 39.2 kg/min), second highest in winter (14.52 kg/min; range: 1.2 – 62.2

kg/min), third highest in fall (12.86 kg/min; range: 1.6 – 41.4 kg/min), and lowest in spring (8.94 kg/min; range: 0.8 – 37.7 kg/min).

In 2008, the *Viking* completed 1405 tows (winter [n=349]; spring [n=414]; summer [n=375]; fall [n=267]). Seasonal comparisons between the global and local regression analyses revealed a significant difference between these two techniques (Table 3.1). The GWR models were a statistically significant improvement over the linear regression model for predicting yellowtail flounder catch rate as indicated by the lower AIC_c values and higher r^2 values. AIC_c values provide a way to measure model performance, and were lower for GWR than for linear models by a range of 18 – 25 points. The coefficient of determination for GWR models ranged between 13 and 35%, whereas linear models ranged between 6 and 14%.

Visual analysis of the local pseudo-r^2 values revealed seasonal differences in the models' explanatory powers (Fig. 3.4). These models explained up to 66% of variance. The strongest model (shown with the highest r^2 values) used the fall dataset, and the weakest used the spring dataset. Generally, within the seasons the strongest explanatory power occurred in NAFO Divisions 3O and 3N.

Results from GWR were analyzed by mapping and visualizing in a Geographic Information System (GIS). Significance of relationships between environmental variables and catch rate was determined using a 95% confidence interval threshold which was applied to the t-value results for each coefficient. Non-significant t-values lay between -1.96 and 1.96, and were marked with an X in Figures 3.5 – 3.8 and 3.11 – 3.14. Significant parameter estimates are represented by the black and white circles in these figures. Positive relationships between yellowtail flounder catch rate and the explanatory variables describe changes in one variable that are associated with changes in the other variable in the same direction. For example, a positive relationship was observed when water depths were shallower (i.e., changed from 80m to 60m) and catch rates decreased (i.e., changed from 20 kg/min to 10 kg/min). Negative relationships describe changes in one variable that are associated with changes in the other variable in the opposite direction. For example, a negative relationship was observed when sediment grain size diminished (i.e., changed from boulder to sand) and catch rate increased (i.e., changed from 10 kg/min to 20 kg/min).

In winter, the *Viking* fished in NAFO Divisions 3O and 3N, however, significance in the relationship between yellowtail flounder catch rate and the environmental variables occurred mostly in 3N (Fig. 3.5). During this season, wind speed had a negative relationship with catch rate (Fig. 3.5a), depth had a mostly positive relationship except for a single tow location in 3O (Fig. 3.5b), sediment had a non-significant relationship with catch rate (Fig. 3.5c), and bottom temperature had a strongly positive relationship (Fig. 3.5d).

During spring, the *Viking* had significant relationships with environmental variables in all three NAFO Divisions (Fig. 3.6). Wind speed and sediment type showed negative relationships (Fig. 3.6a and 3.6c), whereas depth showed positive relationships (Fig. 3.6b). Bottom temperature revealed both negative and positive significant relationships, additionally there appeared to be a spatial dichotomy between the two: positive relationships occurred in northern areas, and negative relationships occurred in southern areas (Fig. 3.6c).

During summer, statistically significant relationships between catch rate and environmental variables occurred in all three NAFO Divisions, the strongest were located in 3O and 3N (Fig. 3.7). Wind speed and sediment type had negative relationships of varying strengths; sediment type revealed stronger relationships with catch rate (Fig. 3.7a and 3.7c). Depth showed positive but weak relationships with catch rate (Fig. 3.7b). Temperature showed strong negative and positive relationships, with an apparent spatial dichotomy: positive relationships occurred further south than negative relationships (Fig. 3.7d).

Lastly, *Viking* catch rates from fall 2008 revealed all negative relationships except for substrate type, which had no significance (Fig. 3.8a-3.8d). Significant catch rates occurred in Divisions 3O and 3N. The three significant variables had differences in strength of relationship with catch rate; temperature was the strongest and wind speed and water depth had roughly even strengths.

In general, the *Viking* parameter estimates were non-stationary and the residuals were randomly distributed throughout the study area as evidenced in the parameter values, the Monte Carlo results, and the global Moran's I results. Summary statistics for seasonal environmental variables revealed broad variance in the parameter values (Tables 3.2 - 3.5). Results from the Monte Carlo significance test showed parameters with significant spatial variation as having p-values <0.05 (Table 3.6). We may therefore conclude that local parameter estimates vary spatially for depth and temperature in any season (p <

0.001). Wind speed varied significantly in spring and fall ($p = 0.03$ for each), but lacked significance in winter and summer ($p = 0.76$ and $p = 0.44$, respectively). Sediment varied significantly in summer and fall ($p < 0.001$ for each), but lacked significance in winter and spring ($p = 0.38$ and $p = 0.07$, respectively). The results from these Monte Carlo tests support the need for a local statistical method to be used in analyzing these data.

3.3.2 *Aqviq*

A broad range of environmental conditions were analyzed during the 2008 fishing season of the *Aqviq* (Fig. 3.9). In winter, average hourly wind speeds were between 1.7 and 19.1 m/s (mean ± SD; 9.5m/s ± 3.7m/s), depth of catch ranged from 44 to 72 m (56.7m ± 4.6m), and bottom water temperatures varied from 1.8 to 3.7°C (2.8° C± 0.3°C). In spring, wind speeds were between 1.7 and 20.1 m/s (8.2m/s ± 3.2m/s), water depths ranged from 40 to 78 m (62.0m ± 6.1m), and bottom water temperatures varied from 0.3 to 4.0°C (2.1° C± 0.9°C). In summer, wind speeds were between 1.1 and 19.0 m/s (6.0m/s ± 2.7m/s), water depths ranged from 51 to 82 m (67.0m ± 7.7m), and bottom water temperatures were the coolest, they varied from 0.0 to 2.8°C (1.2° C± 0.6°C). In fall, wind speeds were between 1.9 and 14.3 m/s (6.6m/s ± 3.0m/s), water depths ranged from 54 to 83 m (66.3m ± 5.1m), and bottom water temperatures varied between 0.7 to 3.3°C (1.9° C± 0.6°C). For all four seasons, yellowtail flounder were mostly caught in areas classified as gravel substrate based on ROXANN acoustic surveys. Mean catch rates were the highest in summer (19.43 kg/min, range: 3.0 – 44.9 kg/min), second highest in winter (17.42 kg/min, range: 1.2 – 52.6 kg/min), third highest in fall (16.07

kg/min, range: 4.4 – 51.2 kg/min), and lowest in spring (12.33 kg/min, range: 0.4 – 33.6 kg/min).

In 2008, the *Aqviq* completed 1563 tows (winter [n=419]; spring [n=454]; summer [n=507]; fall [n=183]). Seasonal comparisons between the global and local regression analysis revealed significant differences between these two techniques (Table 3.7). Based on AIC_c minimization scores and r^2 values for each season, local models were a statistically significant improvement over global models. Analysis of the AIC_c results showed lower values for the GWR models by 22 to 123 points. The coefficient of determination for the GWR model values ranged from 26 to 48% whereas linear models ranged between 1 to 14%.

Visual analysis of the local pseudo-r^2 values revealed seasonal differences in the models' explanatory power (Fig. 3.10). These models explained between 8.9 – 76% of variance. The strongest model (shown with the highest r^2 values) used the fall dataset, and the weakest used the summer dataset. In general, the strongest explanatory power existed in NAFO Division 3N.

In winter 2008, all significant relationships between environmental variables and catch rate occurred in NAFO Division 3N (Fig. 3.11). Wind speed, water depth and sediment type had varying strengths of negative relationships with catch rate: sediment had the strongest relationship, and wind speed and water depth had similar strengths (Fig. 3.11a – 3.11c). Temperature had both strong negative and strong positive relationships, and there appeared to be a spatial dichotomy between the two: negative relationships occurred north of positive relationships (Fig. 3.11d).

In spring, *Aqviq* catch rates revealed significant relationships with all four variables in NAFO Divisions 3LNO (Fig. 3.12). Wind speed, water depth, and temperature showed both negative and positive effects on catch rate (Fig. 3.12a, b, d). Bottom water temperature had the strongest relationships with catch rate regardless of sign; wind speed and water depth had equal strengths of relationships with catch rate. Sediment type showed a strong negative relationship but only in one concentrated area on the Bank (Fig. 3.12c).

In summer, significant relationships with catch rate existed in all three NAFO Divisions (Fig. 3.13). Wind speed had weak negative relationships with catch rate in 3N, and on the border of 3N and 3L (Fig. 3.13a). Water depth had weak positive relationships in 3O and on the border of 3N and 3L (Fig. 3.13b). Sediment type had strong negative relationships in 3O but had very few significant points (Fig.3.13c). Lastly, temperature had both strong negative and positive relationships with catch rate; the negative coefficients occurred primarily in 3O whereas the positive occurred only in 3N (Fig. 3.13d).

In fall, *Aqviq* tows only occurred in NAFO Divisions 3O and 3N (Fig. 3.14). Wind speed, water depth, and temperature all had negative relationships with catch rate (Fig. 3.14a, b, d). Bottom water temperature had the strongest relationship, followed by water depth and then wind speed. Sediment type had a mix of negative and positive coefficients, with the negative occurring to the west of the positive (Fig. 3.14c).

The *Aqviq* parameter estimates displayed non-stationarity and randomly distributed residuals throughout the study area as evidenced by the parameter variance, the Monte

Carlo results, and the global Moran's I results. Summary statistics for each environmental variable in each season revealed broad variance in parameter values (Tables 3.8 – 3.11). Results from the Monte Carlo significance test show parameters with significant spatial variation as having p-values <0.05 (Table 3.12). We may therefore conclude that parameter estimates are not constant within the study for wind speed, water depth and temperature ($p < 0.05$). The only statistically stationary variable (i.e. lacking significant variation) was sediment type in winter ($p = 0.20$). The results from these Monte Carlo tests support the need for a local statistical method to be used in analyzing these data.

3.4 Discussion

The results of this study indicated statistically significant relationships between commercial catch rate and the chosen environmental variables for yellowtail flounder caught by two industry vessels fishing on the Grand Bank in 2008. In general, catch rates for both vessels had negative relationships with wind speed. Positive relationships between water depth and catch rate existed in spring and summer for both vessels; negative relationships existed in fall for both vessels. However, winter patterns were different: the *Viking* catch rate had mostly positive relationships with water depth, whereas the *Aqvik* catch rate had only negative relationships. Substrate type had mostly negative relationships with catch rate of both vessels, although it was the least statistically significant parameter. For both vessels, catch rates showed positive relationships with bottom water temperature in winter, and mixed relationships in other seasons. Additionally, GWR produced statistically improved models over linear regression as demonstrated by the significantly lower AIC_c values as well as the increased r^2 values. In this section I present in-depth examination of these results.

3.4.1 *Wind Speed*

For the *Viking*, wind speed had a significant negative relationship with catch rate throughout the study period. For the *Aqviq*, wind speed also had a significant negative relationship with catch rate in all seasons except for spring where it had both negative and positive relationships. Originally we hypothesized that only negative coefficients would exist between catch rate and wind speed because this variable has previously been shown to affect fish availability, trawl efficiency, and harvesting strategy. Availability for capture is influenced by wind induced movement in the water column, which, when it is rough enough, may be felt at the seafloor causing demersal species to move to deeper water or burrow into the substrate (Harden Jones and Scholes, 1980). Trawl efficiency can be influenced by high winds which affect vessel pitch resulting in surges of the trawl off the ocean bottom (Politis et al., 2012; Queirolo et al., 2012). Stewart et al. (2010) found that changes in trawl shape and contact with the seafloor affects trawl performance by allowing fish to escape, thus lowering catch rate. Lastly, wind speed influences tactical decisions made by captains in order to minimize risk to their gear, vessel, and crew (Queirolo et al., 2012). The *Aqviq* spring fishing season was inconsistent compared with all other seasons: catch rates had both negative and positive relationships with wind speed. Negative relationships fit the previous explanations, but the positive did not.

However, the positive relationships may reflect areas where decreasing catch rates coincided with decreasing wind speeds, which makes sense given spring had the lowest catch rates. As most of our results fit with previous literature, we can conclude that our original hypothesis is correct: catch rate increases with decreasing wind speed.

3.4.2 *Water Depth*

For the *Viking*, water depth had a significant positive relationship with catch rate for all seasons except fall. The *Aqviq* by comparison, revealed positive coefficients in spring and summer, but negative coefficients in winter and fall. Though the relationship sign varied between vessels, the locations of significant parameter coefficients were similar between seasons. For example, in winter the *Viking* fished in a concentrated area on the western side of the Southeast Shoal which was delineated by a cluster of significant positive parameter coefficients. During winter, the *Aqviq* also revealed significant coefficients near this region, though they were negative. Walsh and Brodie (2006) also found the Canadian yellowtail flounder fleet to concentrate their effort in these shallow areas in the winter, where catch per unit effort was the highest. As for the opposite signs of the relationship between the vessels in winter, the significant relationships for the *Viking* appear to occur directly on the edge of the Southeast Shoal – the shallowest area of the Bank – whereas the significant relationships for the *Aqviq* occur northwest of the Shoal. Though this represents only a small difference in depth, it has resulted in varied relationships. Given the homogenous bathymetry of the Grand Bank, changes in depth may be too small to be reflected in our statistical model; alternatively, another factor may be more important than water depth for causing these patterns during winter.

The remaining seasons have similar patterns for both vessels. Spring and summer revealed both vessels moving into deeper and more dispersed fishing locations with resulting positive relationships with catch rate. The abundance of American plaice (*Hippoglossoides platessoides*), a species under a fishing moratorium and listed as threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), increases in summer making it necessary for vessels to move further north and west to avoid excessive bycatch (Walsh and Brodie, 2006). Depth is an important variable for fish survival as it allows for protection, influences habitat, impacts sediment type, and relates to prey distribution (Murawski and Finn, 1988; Walsh et al., 2004; Methratta and Link, 2007; Walsh and Colbourne, 2007). From our results we conclude that in spring and summer catch rate increases with water depth which fits with our original hypothesis. However, the results in fall and winter are contrary to our hypothesis: catch rates decrease in deeper water in fall, and relationships vary in winter suggesting depth may not be an influential variable during this season.

3.4.3 *Sediment Type*

Sediment type was the only variable which lacked statistically significant relationships with catch rate in some seasons of the study. For the *Viking,* sediment was non-significant in winter and fall. While sediment did not lack significant relationships with the *Aqviq* catch rate, there were very few significant parameter coefficients in most seasons. When significant, sediment type generally had negative relationships with catch rate, meaning as sediment size decreased catch rate increased. This supported our original hypothesis. Tows in this study occurred mostly on areas classified as sand and shell hash, gravel, and small rock based on ROXANN acoustic surveys carried out by DFO. These results agree with previous literature which found the habitat of yellowtail flounder on the Grand Bank to include gravelly sand, sand and shell, and rocky sand (Simpson and Walsh, 2004). Substrate type may impact catch rate in two ways. First, yellowtail flounder spatial distribution is influenced by the availability of prey and suitable habitat (Walsh, 1992; Methratta and Link, 2007). In our study, the negative association with larger grain sizes suggested that sand and gravel provide more suitable environments for survival and thus more opportunities to be available for capture. Second, trawl efficiency can be affected by substrate type due to its influence on gear effectiveness by altering net width and contact with the seafloor (Wieland et al., 2009). The lack of statistical significance for the *Viking* in winter and fall may be a consequence of homogeneity of the surficial geology on the Grand Bank. This, coupled with low resolution data, may have resulted in an overly smoothed data layer. However, it may be that sediment does not have a great influence on catch rate distribution. Walsh et al. (2004) found it to have less impact on juvenile yellowtail flounder distribution than depth or temperature. Given our results we can conclude that catch rate increases with decreasing sediment size, but sediment type is the least statistically significant variable in this study.

3.4.4 *Bottom Water Temperature*

Bottom water temperature had a significant albeit varied relationship with catch rate for both the *Viking* and the *Aqviq*. Throughout 2008, temperature parameter coefficients changed in sign (negative and positive) and location. During winter, when mean bottom temperatures were the highest, there were mostly positive relationships with catch rate for both vessels. The warmer water temperatures in winter may affect the swimming ability and endurance of yellowtail flounder, thus enhancing herding and increasing catch rate (Winger et al., 1999). This hypothesis would support the positive relationships seen in our results. Additionally, this warmer water may be reduced to certain regions causing fish aggregations in those areas and thus higher catch rates. Conversely, catch rates for both vessels during summer had negative and positive relationships with temperature: positive relationships (where the two variables changed in the same direction) occurred in shallow areas near the Southeast Shoal, and negative relationships (where the two variables changed in the opposite direction) occurred to the north and west. Bottom water temperatures were cooler in summer than winter, therefore, we speculate that the positive relationships reflect decreased catch rate due to lower temperatures consistent with the temperature-dependent herding of flatfish predicted by Winger et al. (1999). Additionally, the absence of warm water pockets may have lead to fewer aggregated fish and lower catch rates. During summer, the negative relationships occurred in northern regions for the *Viking* and in western regions for the *Aqviq*; these two areas have been noted in previous literature as places to harvest in order to avoid American plaice bycatch (Brodie et al., 2006). We may conclude that, though temperature is low and herding abilities are decreased, the areas to the north and west of central 3N provide superior catch rates during summer resulting in a negative relationship with temperature. Our original hypothesis is supported in winter: catch rate increases with increasing bottom water temperature. However, this does not hold for other seasons when catch rate may be more dependent on external factors such as bycatch avoidance.

3.4.5 *Viking and Aqviq*

Differences observed between the two vessels may arise from variation between captains' strategies or differences in gear used. The two captains running the *Aqviq* and *Viking* are both experienced fishers, having fished for yellowtail flounder since the 1990s, but they likely have different fishing strategies. Effort allocation (Hilborn, 1985), or deciding when and where to fish, is an element of fleet dynamics that influences the spatial distribution of a fishery. The dynamic choices made by captains are reflected in the patterns seen in this study. Additionally, while the two vessels use the same mesh dimensions and similar trawl gear, captains may make individual modifications to the gear to meet their needs (G. Thorbjornsson, personal communication, March 8, 2012). Therefore some variation in catch rates might occur even when the vessels are harvesting in proximal locations at similar times of the year.

3.4.6 *Geographically Weighted Regression*

GWR, as indicated by our results, provided better models for the relationships between commercial catch rate of yellowtail flounder and the chosen environmental variables as compared to a global linear regression. This improved performance is evident in the significantly lower AIC_c values and higher proportion of explained variance (r^2). The Monte Carlo significance test was used to examine the spatial variation of each predictor variable in the models. The p values in tables 3.6 and 3.12 indicated that there were models in which either wind speed, sediment, or both are not spatially non-stationary. However, Brunsdon et al. (1998) points out that the Monte Carlo significance test is not without its issues: it may be better to know how a variable changes over space, instead of the mere fact that it changes. They propose checking the variability of the coefficients against their standard errors, a method also used by Windle et al. (2009). Spatial non-stationarity is reflected by a ratio >1 when comparing the coefficient inter-quartile range (the difference between the lower and upper quartile of the coefficients) to twice its standard error (Brunsdon et al., 1998). This additional comparison still results in some stationarity of variables which may be due to the choice of bandwidth. In GWR, a bandwidth is chosen by minimizing the AIC_c but it still may not be the right scale for detecting variability in spatial stationarity of relationships between variables (Windle et al., 2009). The ability of GWR to explore spatial non-stationarity in addition to the benefits of visualizing parameter coefficients supports the use of GWR in this study.

3.4.7 *Limitations to Approach*

Several issues in data collection and manipulation should be considered when interpreting these results. All environmental variables were collected independently of the commercial catch rate data, and thus, at different spatial and temporal locations. In order to associate the dependent and independent variables, surfaces were interpolated and points were extracted, however, interpolation – the prediction of un-sampled points using sampled data – may be subject to unknown error. Short of ground truthing the created surfaces, every attempt was made to insure they were accurate and within reason by manually checking the layers and comparing them with other environmental research from the Grand Bank. Additionally, it should be noted that certain key variables, such as predator and prey distribution, bycatch, and trawl door spread (trawl door geometry changes throughout a tow and can impact catch) were beyond the scope of this project but may have added to the predictive powers of the GWR model. This study is limited temporally with only a single year of data. Multiyear analysis may have provided a clearer picture of changing relationships between catch rate and environmental variables. The use of industry-dependent data also posed hurdles: logbook data are biased because they are not collected using scientific methods. Also, they may contain errors and inaccuracies. Furthermore, although the VIF between variables was always less than 3 (convention follows that a VIF over 4 warrants further investigation), there still may have been some multicollinearity between variables. Lastly, the use of GWR was not without drawbacks. The local nature of GWR results prohibits the prediction of catch rate beyond this specific study area. GWR has great potential for use in fisheries research, but analysts should be aware of the possible limitations. Future studies of commercial yellowtail flounder catch would benefit from *in situ* data collection, ground truthing sediment classifications, and the addition of other key data layers.

3.5 Conclusion

In summary, statistically significant relationships existed between all environmental variables and catch rate of both vessels. These relationships varied in strength, direction, and location between seasons and boats. In general, *Viking* and *Aqviq* catch rates had negative relationships with wind speed (i.e., as wind speed increased, catch rate decreased). Positive relationships between water depth and catch rate existed in spring and summer for both vessels (i.e., as water depth increases, catch rate increases); negative relationships between depth and catch rate existed in fall for both vessels (i.e., as depth increases, catch rate decreases). Conflicting relationships between water depth and catch rate were seen in winter for both vessels, therefore other variables may be more statistically significant during this season. Substrate type was the least statistically significant variable. For both vessels, catch rate showed positive relationships with bottom water temperature in winter, but mixed relationships in other seasons; external factors, such as bycatch avoidance, may be more influential on catch rate. Through this research we quantified catch rate patterns in the fishery and determined environmental variables that affect them.

Industry-dependent data were a crucial part of this project. We used commercial logbooks which are a form of Volunteered Geographic Information (VGI), meaning they contain geographic data collected voluntarily by non-specialists who, though they were trained fishers, were untrained in data collection (Goodchild, 2007). By avoiding scientific protocol these data are subject to concerns of data quality and credibility (Flanagin and Metzger, 2008). However, VGI also has the potential to cheaply and efficiently aid scientific research (Connors et al., 2011). An increasing number of studies are now using this kind of data to address questions of scientific relevance (Pattengill-Semmens and Semmens, 2003; Kalabokidis et al., 2008; Arrigo, 2011). In order to operate an efficient and sustainable industry it is recommended that industry better understand yellowtail flounder and their environment. The systematic collection of other VGI such as sea state, water temperature, substrate type and turbidity by commercial vessels, using established protocols wherever possible and practical, will strengthen this knowledge. Given the small number of data collectors (i.e., captains and first mates), training in data collection can be done to ensure quality and credibility, and steps can be taken to ensure data accuracy. It is recommended that more research be done into the steps needed for industry to collect, manage and use more environmental data on a voluntary basis.

Table 3.1: Comparison of linear regressions and GWR model fit for each season of commercial yellowtail flounder catch rate for the *Viking* in 2008.

Model	N	AIC_c Linear	AIC_c GWR	r^2 Linear	r^2 GWR
Winter	349	2365.2	2342.6	7%	22%
Spring	414	2438.6	2415.7	6%	13%
Summer	375	2191.4	2165.8	8%	26%
Fall	267	1732.3	1714.2	14%	35%

Table 3.2: Summary statistics for GWR parameter coefficients for the *Viking* during winter 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-193.31	-88.90	-51.25	-37.60	89.93	11.53
Wind Speed	-0.57	-0.40	-0.34	-0.28	-0.04	0.11
Depth	-0.62	-0.32	0.19	0.41	1.55	0.12
Sediment	-1.53	-0.84	-0.41	0.35	2.35	0.69
Temperature	-21.60	9.41	18.34	37.78	92.33	1.91

Table 3.3: Summary statistics for GWR parameter coefficients for the *Viking* during spring 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-8.03	2.16	9.37	18.93	24.79	2.55
Wind Speed	-0.36	-0.07	0.05	0.06	0.11	0.07
Depth	-0.22	-0.10	0.01	0.07	0.23	0.04
Sediment	-1.28	0.35	0.54	0.74	0.97	0.28
Temperature	-4.09	-1.45	-0.98	0.30	1.59	0.24

Table 3.4: Summary statistics for GWR parameter coefficients for the *Viking* during summer 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-28.27	-9.38	-2.67	9.38	45.32	3.03
Wind Speed	-0.89	-0.28	-0.22	-0.07	0.01	0.11
Depth	-0.38	0.10	0.25	0.39	0.80	0.04
Sediment	-2.80	-0.69	-0.12	1.11	1.91	0.29
Temperature	-21.72	-2.22	-1.19	4.28	8.32	0.59

Table 3.5: Summary statistics for GWR parameter coefficients for the *Viking* during fall 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-32.10	-1.38	18.00	164.28	177.33	4.80
Wind Speed	-1.48	-0.85	-0.77	-0.25	-0.09	0.13
Depth	-1.55	-1.34	0.01	0.35	0.70	0.07
Sediment	-10.24	-7.44	-2.10	0.80	3.76	0.71
Temperature	-21.38	-20.73	-3.63	-0.31	13.17	0.66

Table 3.6: Tests for local non-stationarity of parameter estimates for the *Viking* in winter, spring, summer and fall 2008. ** = Significant at 1%. * = Significant at 5%.

	P Value			
Variable	Winter	Spring	Summer	Fall
Intercept	0.00000**	0.00000**	0.00000**	0.00000**
Wind Speed	0.76000	0.03000*	0.44000	0.03000*
Depth	0.00000**	0.00000**	0.00000**	0.00000**
Sediment	0.38000	0.07000	0.00000**	0.00000**
Temperature	0.00000**	0.00000**	0.00000**	0.00000**

Table 3.7: Comparison of linear regression and GWR model fit as applied to yellowtail flounder commercial catch rate on the *Aqviq* in 2008.

Model	N	AIC_c Linear	AIC_c GWR	r^2 Linear	r^2 GWR
Winter	419	3050.5	2971.5	1%	30%
Spring	454	2913.0	2789.8	3%	38%
Summer	507	3185.7	3123.7	7%	26%
Fall	183	1222.5	1199.8	14%	48%

Table 3.8: Summary statistics for GWR parameter coefficients for the *Aqviq* during winter 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-484.08	-142.28	-61.25	31.36	200.20	13.08
Wind Speed	-1.17	-0.24	-0.12	-0.03	0.49	0.13
Depth	-1.98	-0.85	-0.46	0.28	0.98	0.13
Sediment	-7.09	-2.32	-0.36	0.50	3.92	0.71
Temperature	-47.02	17.76	24.85	50.13	198.67	2.16

Table 3.9: Summary statistics for GWR parameter coefficients for the *Aqviq* during spring 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-85.75	-37.81	-6.31	4.06	57.63	3.10
Wind Speed	-0.85	-0.50	-0.01	0.21	1.05	0.09
Depth	-0.88	0.01	0.28	0.79	1.35	0.05
Sediment	-5.08	-0.03	0.76	1.18	3.45	0.37
Temperature	-9.45	-0.92	0.49	2.41	16.42	0.31

Table 3.10: Summary statistics for GWR parameter coefficients for the *Aqviq* during summer 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-43.07	-9.21	-1.93	5.09	42.07	3.31
Wind Speed	-0.80	-0.64	-0.41	-0.27	0.44	0.10
Depth	-0.23	0.13	0.32	0.41	0.80	0.04
Sediment	-2.42	-0.62	-0.44	0.06	1.97	0.34
Temperature	-13.91	-4.86	2.39	7.76	33.14	0.68

Table 3.11: Summary statistics for GWR parameter coefficients for the *Aqviq* during fall 2008. S.E.= Standard error of parameter estimate.

Variable	Minimum	Lower quartile	Median	Upper Quartile	Maximum	S.E.
Intercept	-68.59	62.94	134.81	203.61	242.95	8.31
Wind Speed	-1.66	-0.12	0.04	0.22	0.59	0.19
Depth	-3.24	-2.50	-1.58	-0.18	1.31	0.14
Sediment	-8.52	-4.65	-3.47	-0.61	13.26	0.86
Temperature	-23.57	-18.38	-9.84	-3.98	2.94	1.14

Table 3.12: Tests for local non-stationarity of parameter estimates for the *Aqviq* in winter, spring, summer and fall 2008. ** = Significant at.1%. * = Significant at 5%.

	P Value			
Variable	Winter	Spring	Summer	Fall
Intercept	0.00000**	0.00000**	0.00000**	0.00000**
Wind Speed	0.00000**	0.01000*	0.00000**	0.04000*
Depth	0.00000**	0.00000**	0.00000**	0.00000**
Sediment	0.20000	0.04000*	0.03000*	0.01000*
Temperature	0.00000**	0.00000**	0.00000**	0.00000**

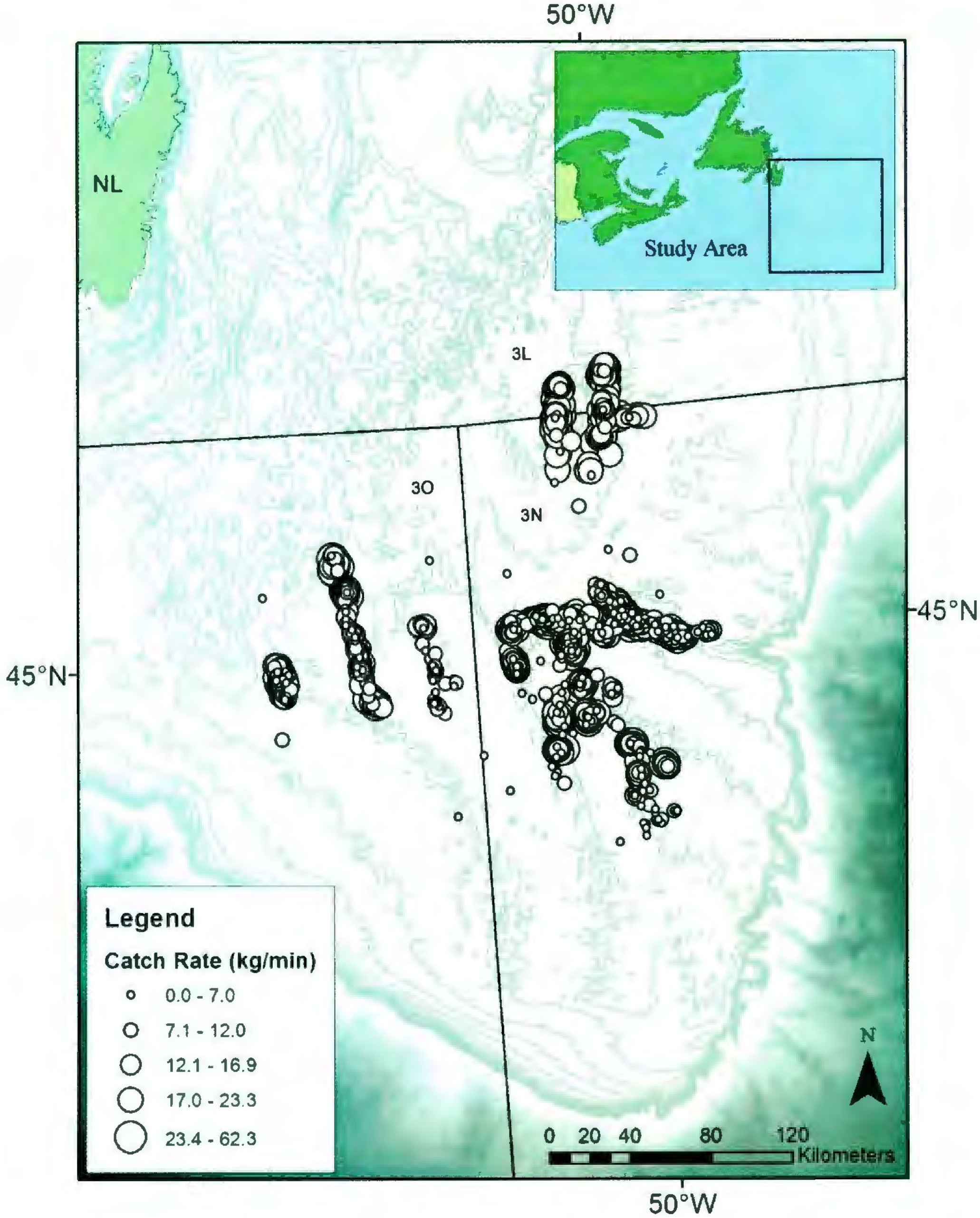

Figure 3.1: Map of Newfoundland (insert), showing the study area location in the Atlantic Ocean. Locations of *Viking* tows are distributed between NAFO Divisions 3LNO. Symbol size denotes catch rate (kg/min).

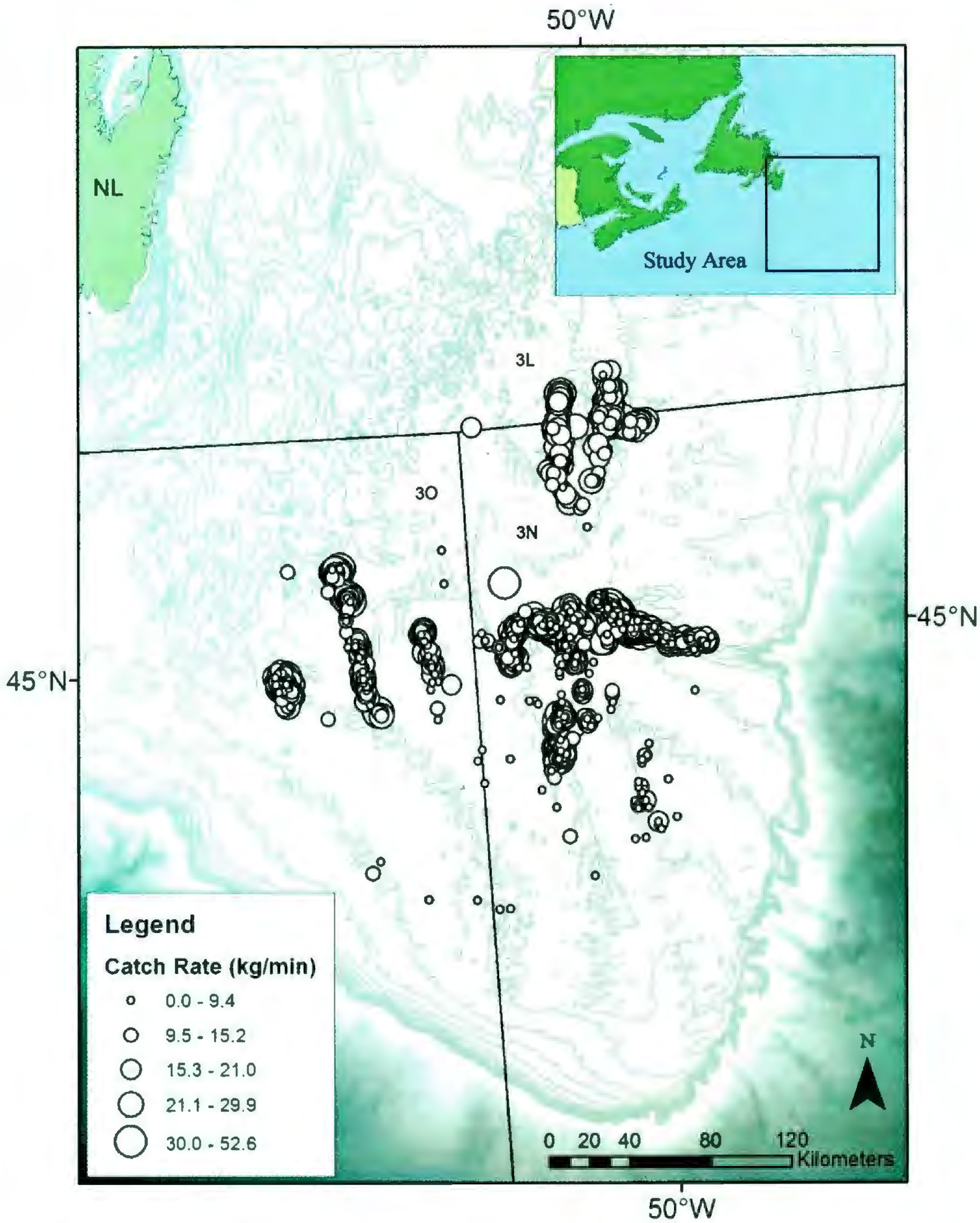

Figure 3.2: Map of Newfoundland (insert), showing the study area location in the Atlantic Ocean. Locations of *Aqviq* tows are distributed between NAFO Divisions 3LNO. Symbol size denotes catch rate (kg/min).

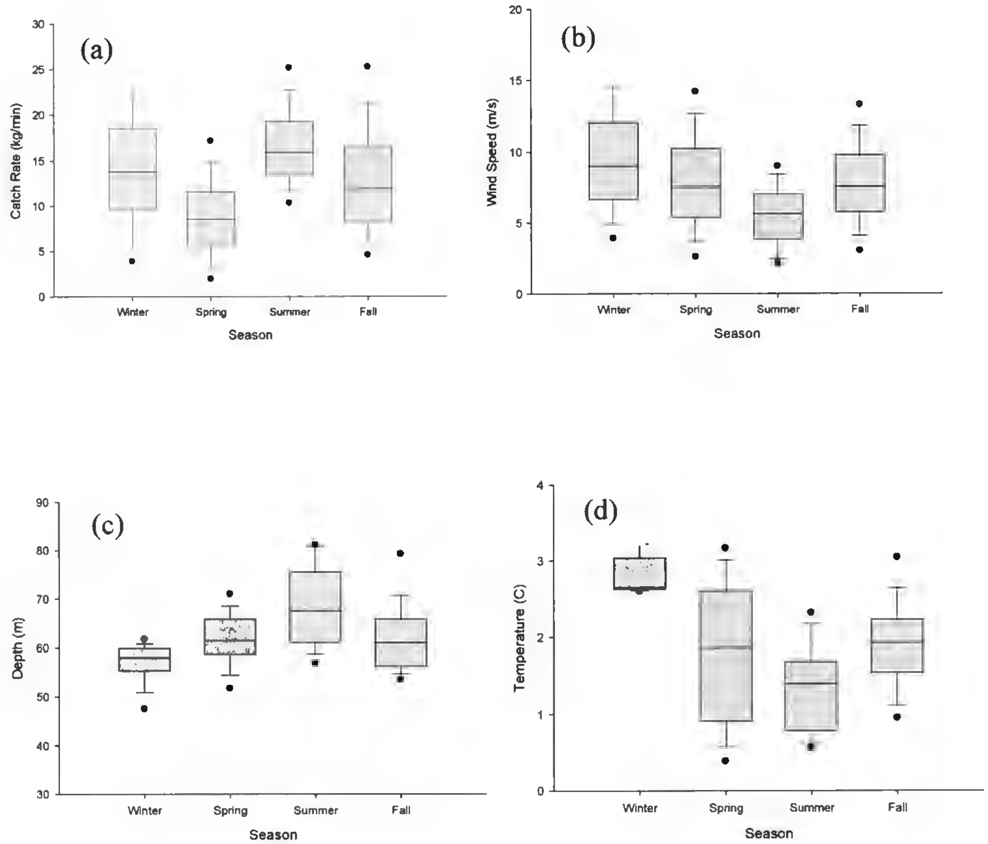

Figure 3.3: *Viking* seasonal median values for (a) catch rate, (b) wind speed (1 m/s = 1.94 knots), (c) depth and (d) bottom water temperature. As sediment is categorical, it was not included. Black dots represent 5th/95th percentile outliers.

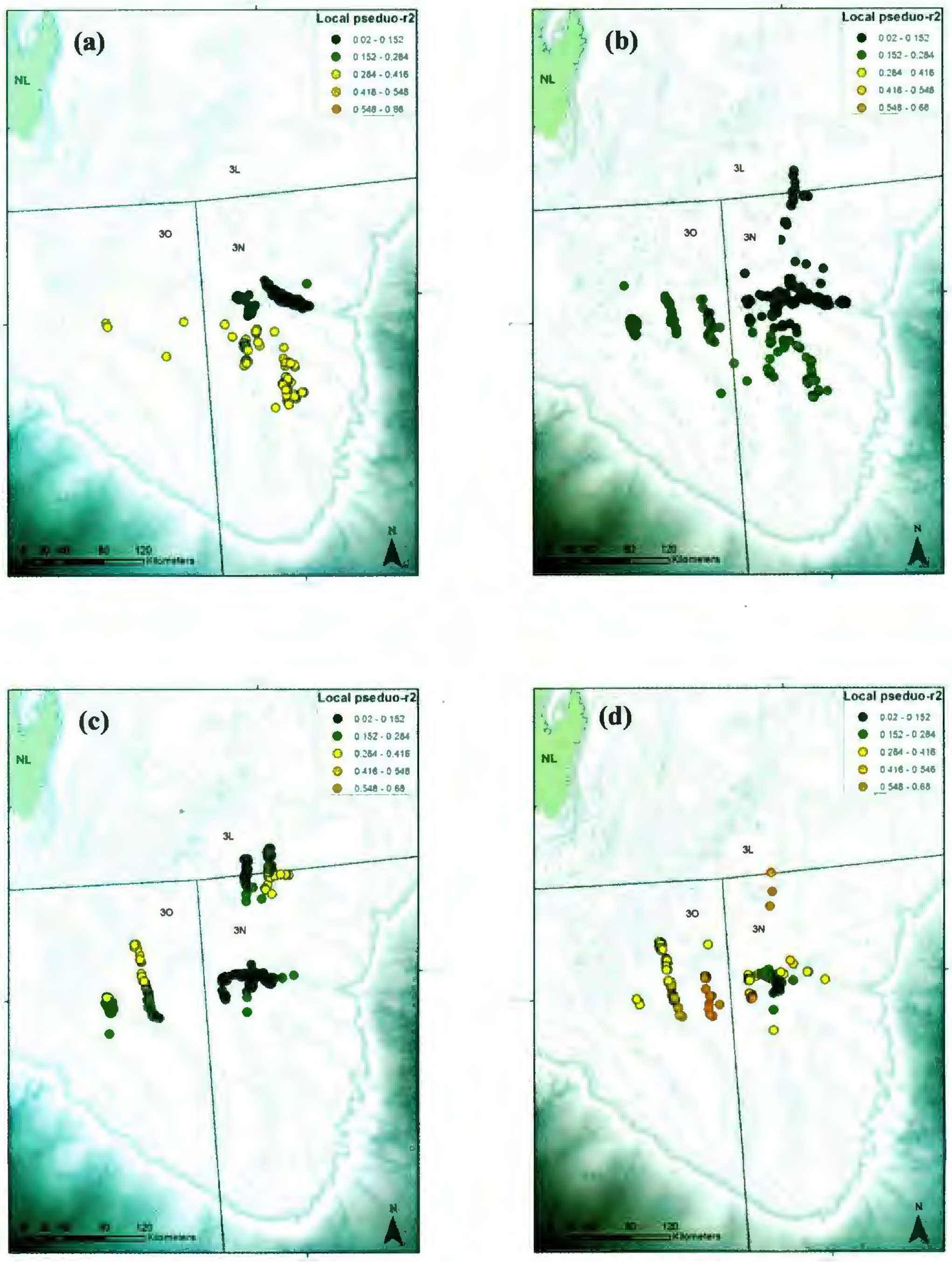

Figure 3.4: Local pseudo r^2 values from the *Viking* tows of 2008 for (a) winter, (b) spring, (c) summer, and (d) fall.

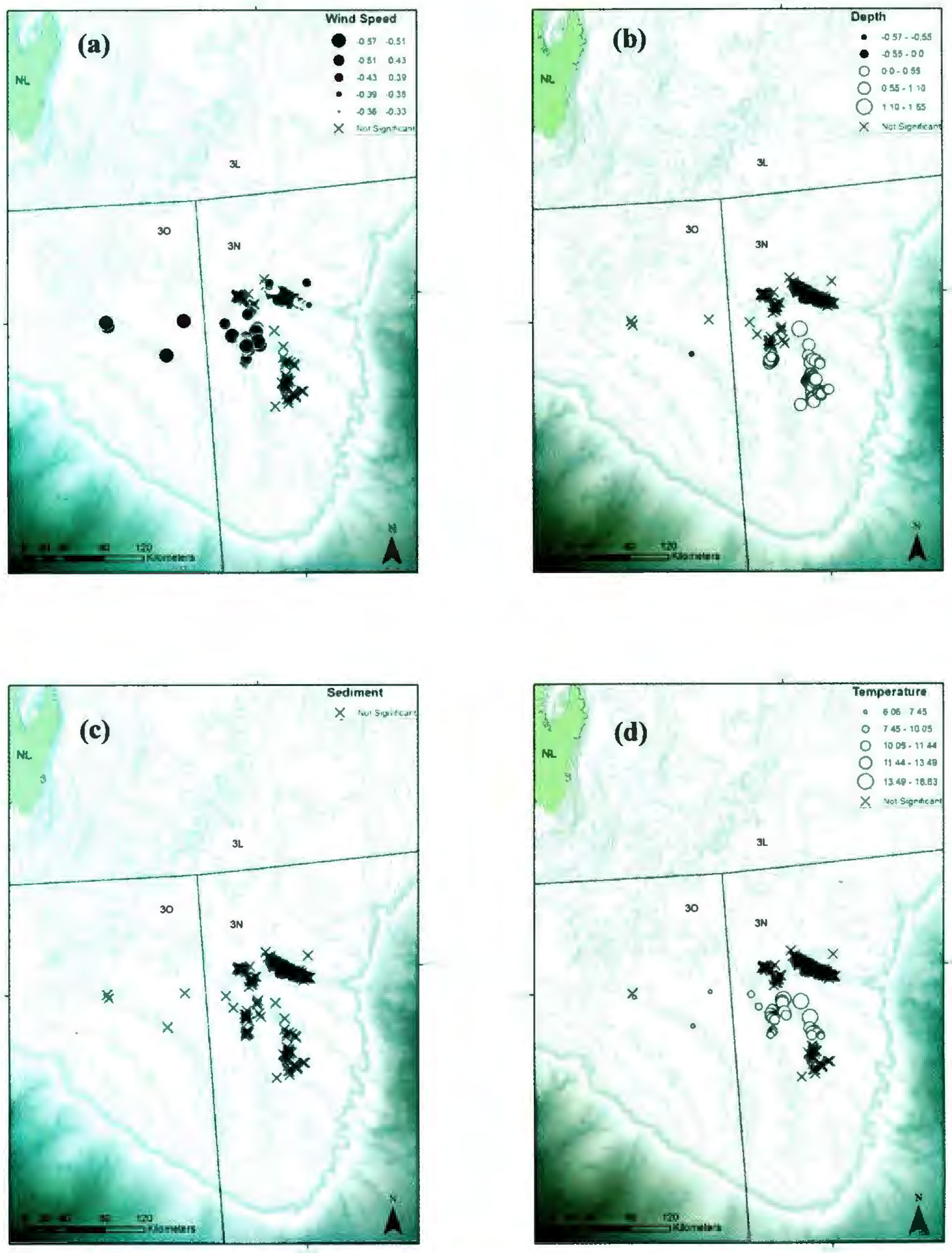

Figure 3.5: Local coefficient estimates for the Viking in winter 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

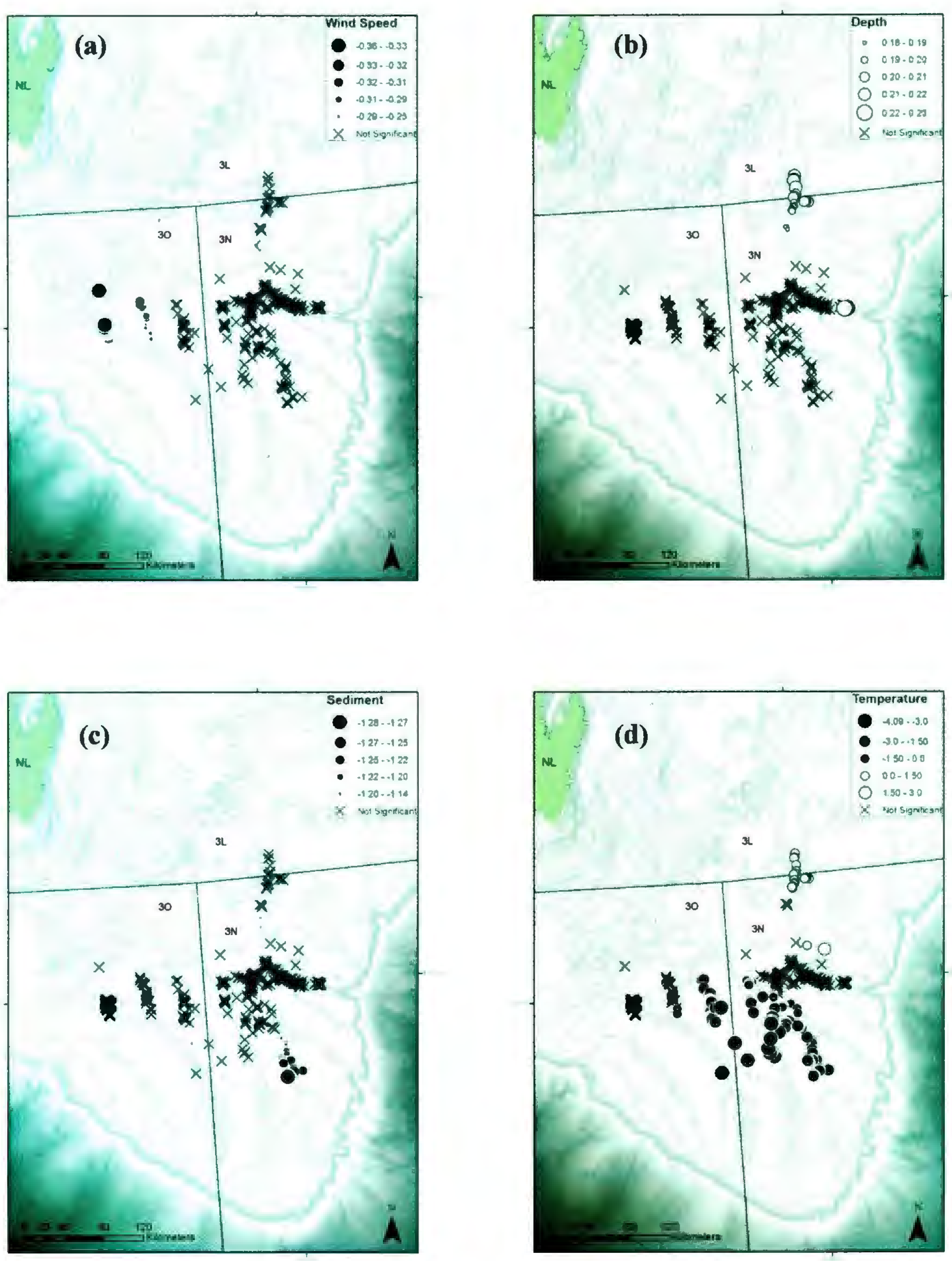

Figure 3.6: Local coefficient estimates for the Viking in spring 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

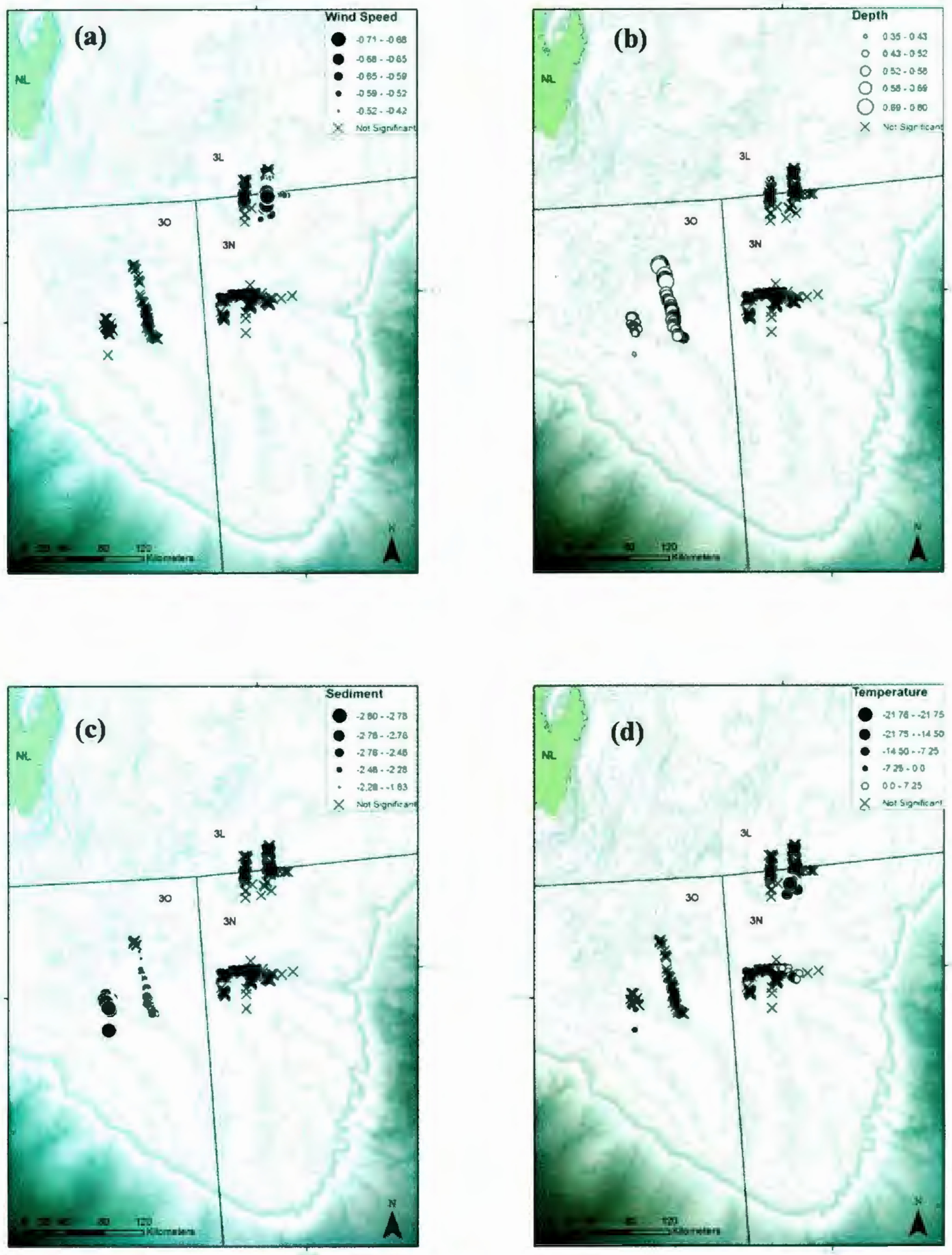

Figure 3.7: Local coefficient estimates for the Viking in summer 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

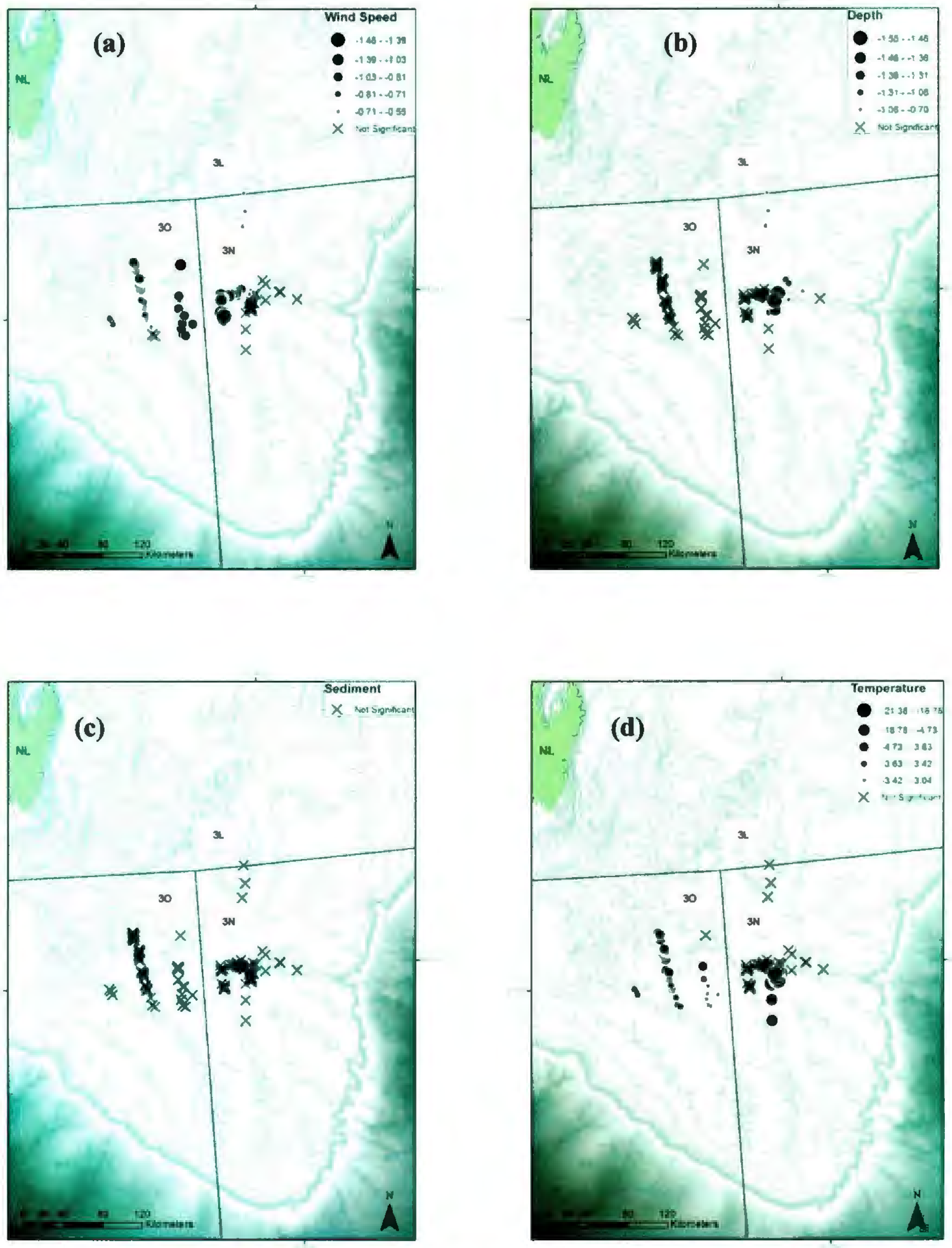

Figure 3.8: Local coefficient estimates for the Viking in fall 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

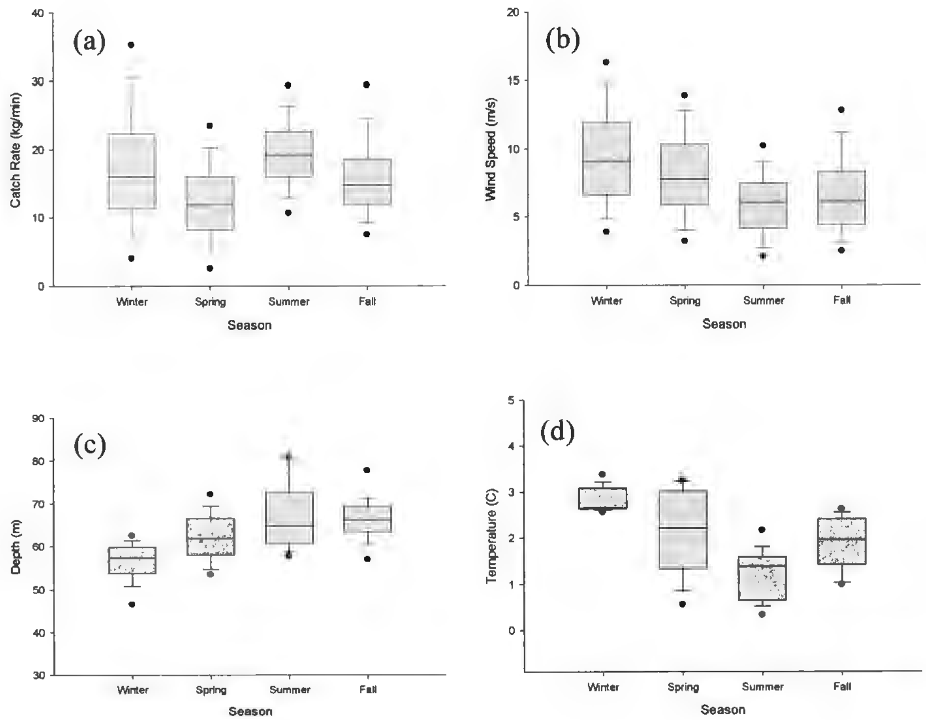

Figure 3.9: *Aqviq* seasonal median values for (a) catch rate, (b) wind speed (1 m/s = 1.94 knots), (c) depth and (d) bottom water temperature. As sediment is categorical, it was not included. Black dots represent $5^{th}/95^{th}$ percentile outliers.

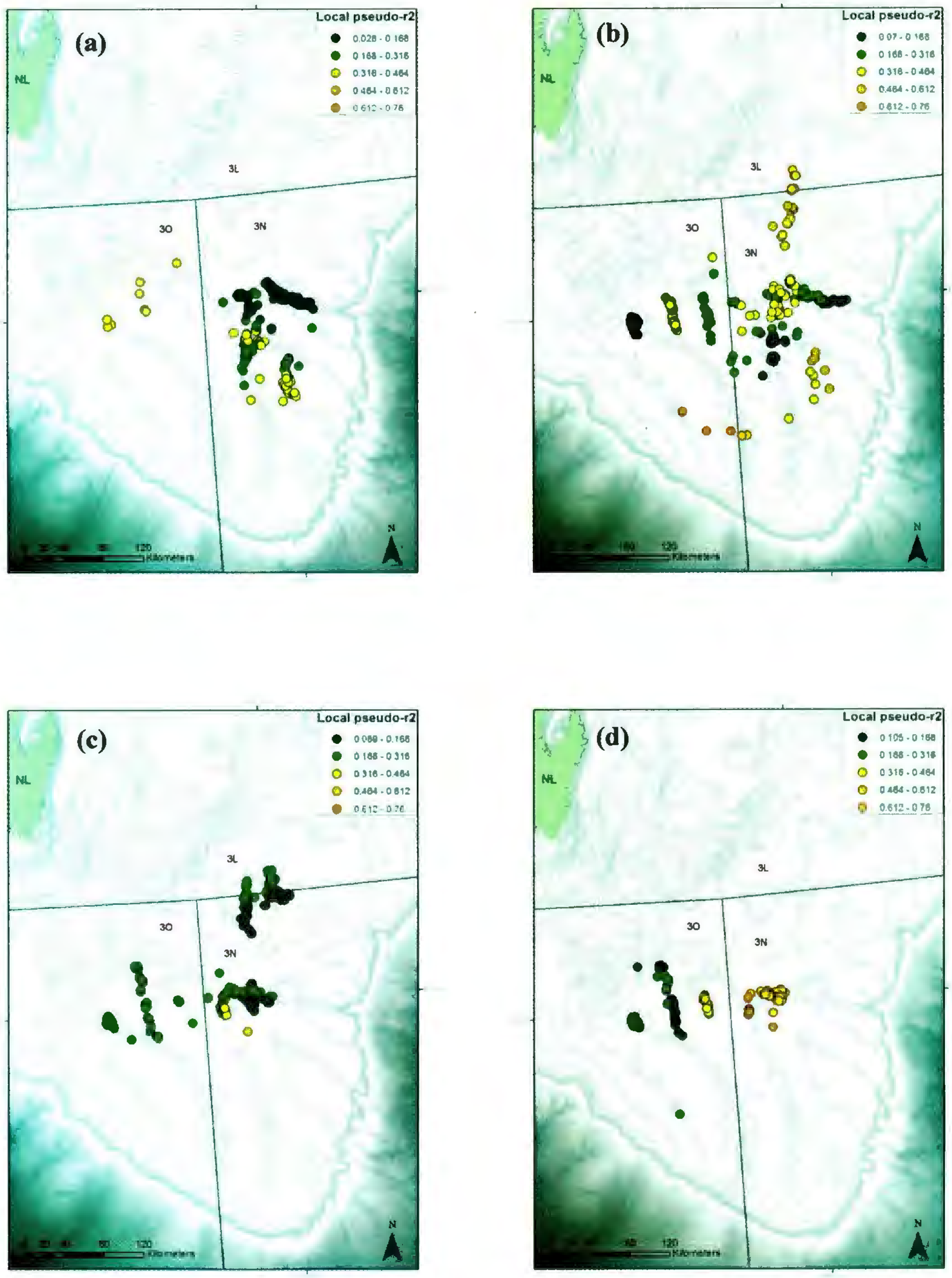

Figure 3.10: Local pseudo r2 values from the Aqviq tows of 2008 for (a) winter, (b) spring, (c) summer, and (d) fall.

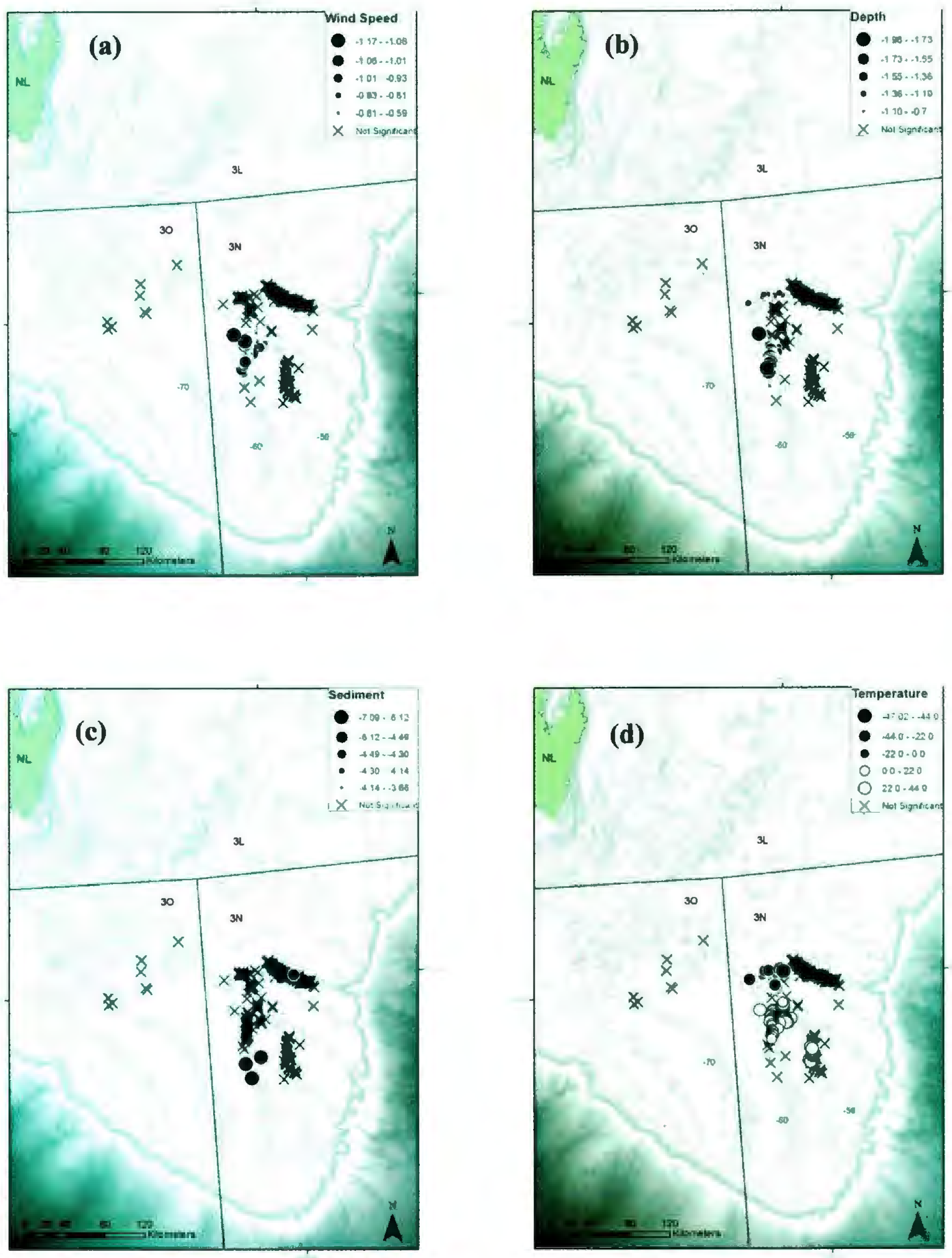

Figure 3.11: Local coefficient estimates for the Aqviq in winter 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

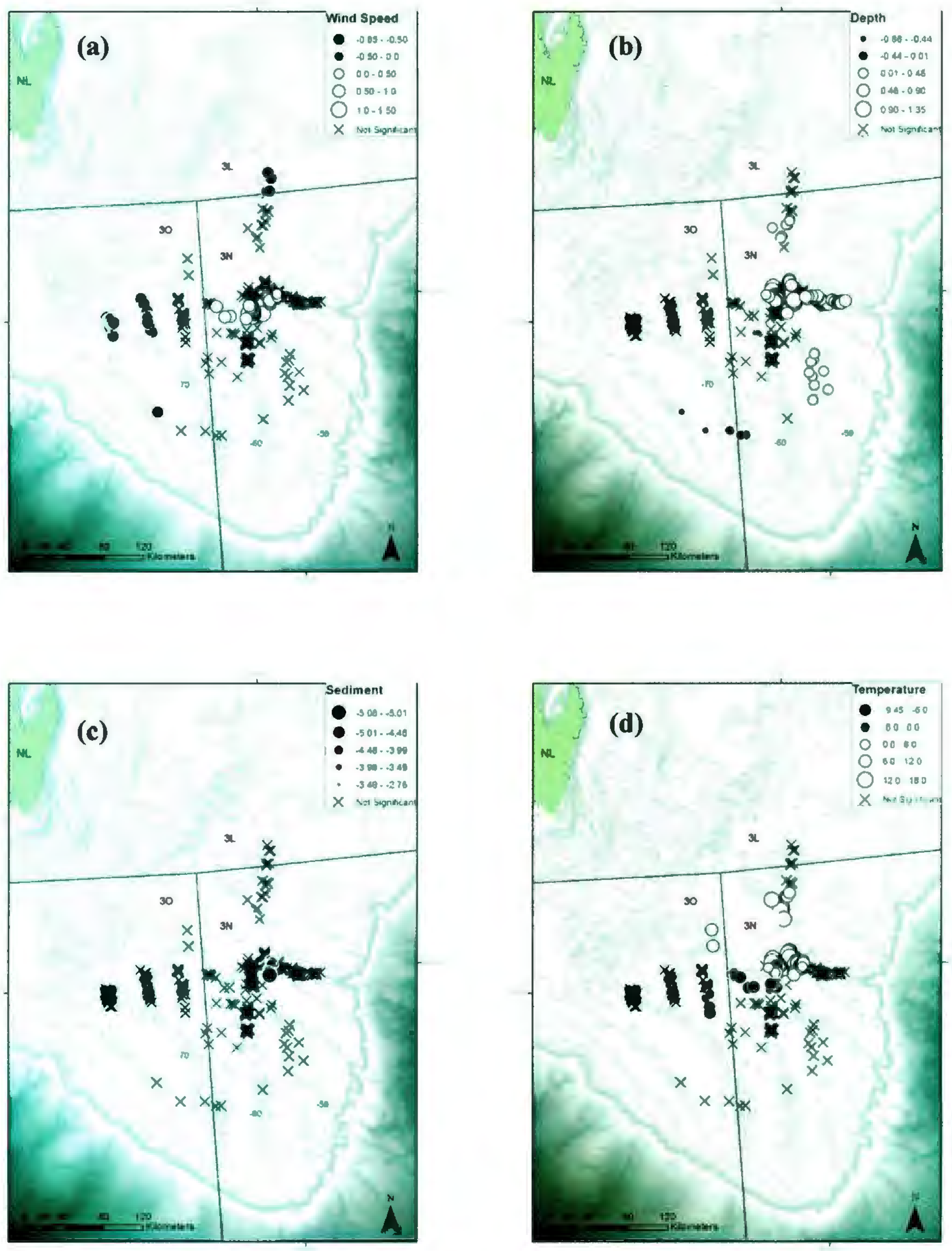

Figure 3.12: Local coefficient estimates for the Aqviq in spring 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as “x”. Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

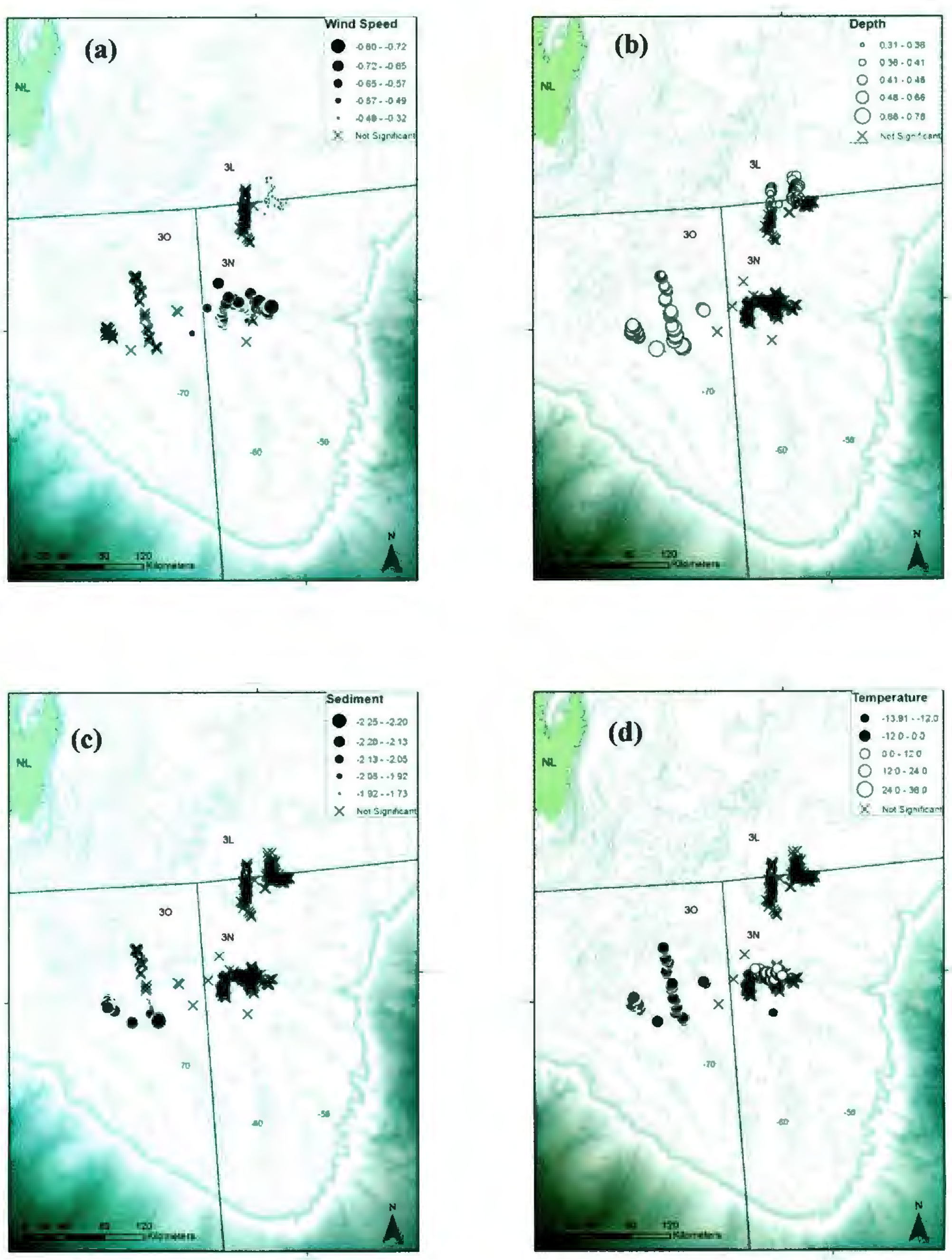

Figure 3.13: Local coefficient estimates for the Aqviq in summer 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as "x". Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

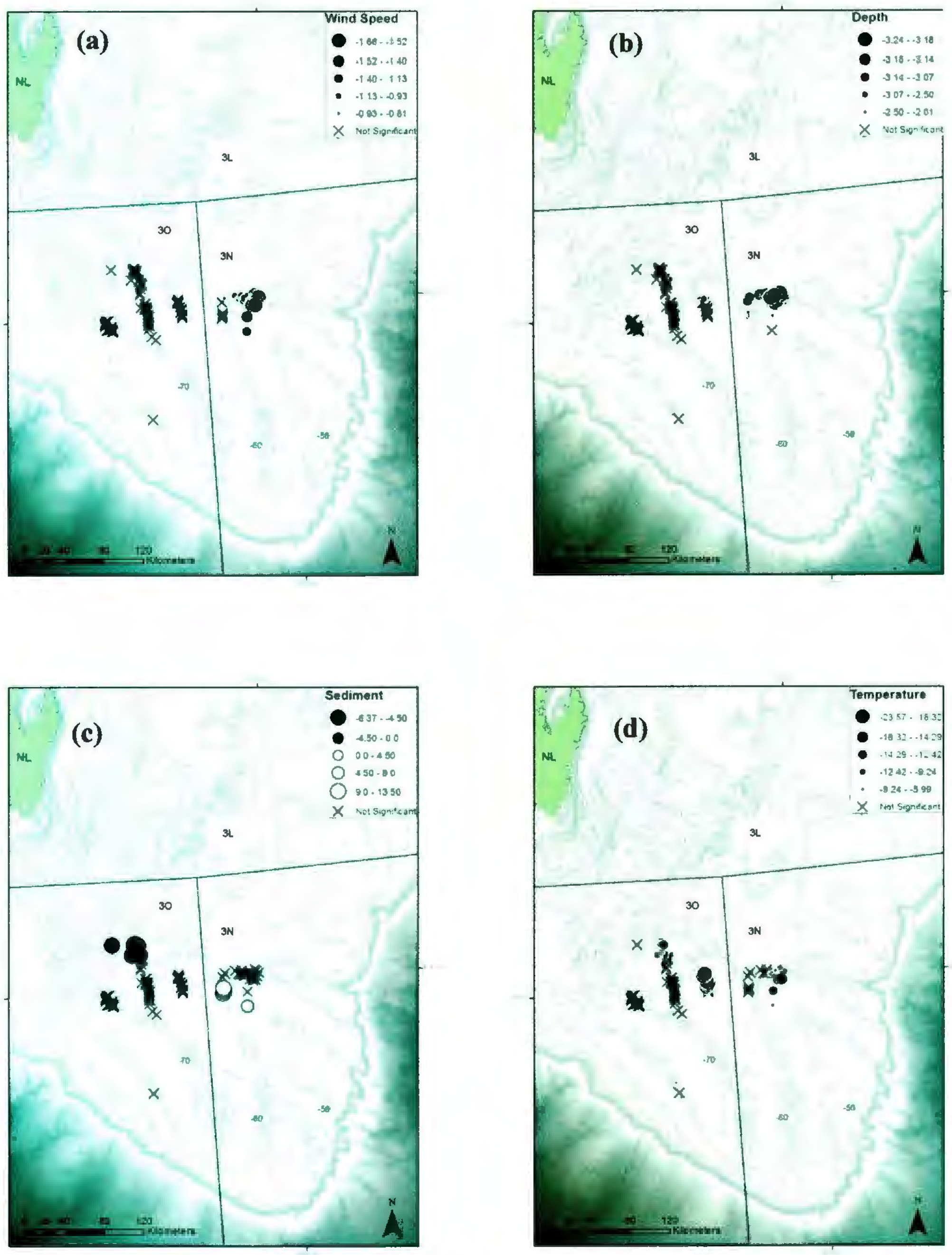

Figure 3.14: Local coefficient estimates for the Aqviq in fall 2008 for (a) wind speed, (b) depth, (c) sediment, and (d) temperature as predictors of yellowtail flounder commercial catch rate. Significance was determined using a 95% threshold, which is shown as “x”. Positive values are shown as white circles and negative values are black circles. See map legend for symbol value.

Chapter 4: Summary

The objective of this study was to examine the influence of temporal and environmental conditions on commercial catch rate of yellowtail flounder (*Limanda ferruginea*) on the Grand Bank of Newfoundland and Labrador, Canada. The temporal analysis (Chapter 2) quantified the variation in catch rate among times of day and seasons using historical logbooks from the *F/V Aqviq* and *F/V Mersey Viking*. Results revealed that daytime and nighttime catch rates were higher in winter and summer for both vessels, and catch rates were higher during nighttime compared to daytime. The original hypothesis stated that catch rates would be highest during the night and during seasons with little sunlight due to the influence of low ambient light levels on yellowtail flounder catchability. Analysis of the results points to a combination of environmental causes (i.e., temperature and sea state) in addition to light availability as contributors to high catch rates. By quantifying the temporal patterns in this fishery, we have outlined the optimum fishing periods for industry.

Environmental analysis (Chapter 3) investigated the relationships between commercial catch rate and environmental variables using spatial statistics novel to fisheries research, in order to identify influential habitat parameters important to successful harvesting. A local spatial statistic, Geographically Weighted Regression (GWR) analysis, was used to determine the strength of relationship between catch rate and wind speed, water depth, sediment type, and bottom water temperature. The outputs of this analysis, which can be mapped, also provided visualization of strong statistical relationship locations in the study area. The results suggested that high catch rates were related to low wind speeds, shallow fishing depths in winter, deep fishing depths in other seasons, fine-grained sediment type, warm bottom water temperatures in winter and cool bottom water temperatures in summer. Additionally, GWR was compared with global linear regression analysis. Findings were consistent with Windle (2009) who found an improvement of GWR over global linear regression analysis. The combination of this method with more data collected *in situ* has the potential to be useful in predicting yellowtail flounder commercial catch rates. Therefore, the equipping of OCI vessels with environmental data collection devices will provide more opportunities for future studies to enhance the spatial understanding of this species, efficiency of harvesting, and sustainability of industry.

The limitations to the approaches in this thesis should be considered when interpreting the results. Both experimental chapters (Chapters 2 and 3) were limited by using only one year of data, a result of gaps in historical logbooks. In Chapter 2, another limitation was that temporal patterns may have been masked by other external factors impacting catch rate. These factors include the company's avoidance of bycatch, undersize fish, and poor quality fish, as well as their dependence on market conditions. All of these can introduce bias in temporal and spatial patterns of commercial logbook data, masking effects of other factors.

Data limitations also arose in Chapter 3. Due to the industry-independent collection of environmental data, independent variables varied spatially and temporally from logbook data. This resulted in the necessity of interpolation, a process subject to unknown error. Additionally, certain key variables were beyond the scope of this study but would have enhanced the predictive powers of the GWR model. These variables include predator and prey distribution, bycatch levels, and trawl-door spread. The used variables may have been correlated, although multi-collinearity analysis indicated that they were not. Lastly, while GWR offered many benefits, such as the ability to visualize the data and compare relationships on a local scale, the localized nature of the results prohibit prediction of catch rate beyond the study area.

The use of industry logbooks as the source of dependent variables in both Chapters 2 and 3 posed interesting challenges, but also provided many benefits. The logbooks were a form of Volunteered Geographic Information (VGI) because they were a compilation of data that were not randomly stratified or collected under scientific control; instead they were a voluntary creation of geographic information by scientifically untrained individuals (Goodchild, 2007). The use of VGI presents some hurdles such as concerns of data quality and credibility (Flanagin and Metzger, 2008), but it can also be beneficial for increasing the quantity of available data in a cost efficient way and by involving citizens in decision making (Connors et al., 2011). By collecting environmental data aboard industry vessels, either through hull-mounted recording systems or additional fields to the hand-written logbooks, captains are contributing to the over-all knowledge surrounding the fishery and taking part in its sustainability. This thesis represents the first study in the relationships between commercial catch rate of OCI vessels and temporal and environmental variables, and it outlines the importance of analyzing these factors for an efficient and sustainable industry.

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