Multidisciplinary perspectives on Atlantic halibut spawning behavior and vulnerability in the Gulf of St. Lawrence

by © Rachel C. Marshall

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Abstract

Marine species' distribution and reproduction is valuable information for fisheries management and conservation. In this thesis, spawning of Atlantic halibut, a commercially important flatfish showing increasing abundance in the Gulf of St. Lawrence, is characterized using pop-up satellite archival tags, and potential ocean industry impacts to the halibut population are identified with fish harvesters' knowledge. Halibut displayed extreme rises off the seafloor, interpreted as spawning behavior, from January to late April. The date of the first spawning rise was negatively correlated with December to mid-January water temperatures. The number of female spawning rises, assumed to represent egg batches, was independent of fish length. Halibut harvesters presented with findings of halibut spawning and migration identified industries that could impact the halibut population, at the forefront being a developing redfish trawl fishery. Harvesters participating in semi-structured interviews expressed concern that halibut bycatch in a redfish fishery would reduce the current halibut abundance, which they attributed to the reduction of Gulf trawling and halibut bycatch since the 1990s. The integration of electronic tagging and fish harvesters' knowledge highlights these halibut population vulnerabilities for ocean managers to incorporate into future spatial planning and management of the Gulf of St. Lawrence.

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List of Abbreviations

ACPG	L'association des Capitaines-Propriétaires de la Gaspésie
AIC	Akaike Information Criteria
cm	Centimeter(s)
CPUE	Catch Per Unit Effort
DFO	Fisheries and Ocean Canada
FFAW	Fish, Food and Allied Workers union
FHK	Fish harvesters' Knowledge
ft	Feet
GDD	Growing Degree Day
GLM	Generalized Linear Model
ICEHR	Interdisciplinary Committee on Ethics in Human Research
kg	Kilogram(s)
lbs	Pounds
m	Meter(s)
mm	Millimeter(s)
NAFO	Northwest Atlantic Fisheries Organization
NSERC	Natural Sciences and Engineering Research Council
PEI	Prince Edward Island
PEIFA	Prince Edward Island Fishermen's Association
PSAT	Pop-up Satellite Archival Tag
USA	United States of America

Co-Authorship Statement

Data Sources

The research presented in this thesis was conducted by Rachel Marshall under the guidance of supervisors Dr. Arnault Le Bris and Dr. Jonathan Fisher, and supervisory committee member Dr. Erin Carruthers. Electronic tagging data were collected as part of several research projects led by Drs. Dominique Robert, Jonathan Fisher, and Arnault Le Bris. Additional electronic tagging data from the southern Gulf of St. Lawrence in 2013 and 2014 were provided by the PEI Fishermen's Association and the University of PEI masters student Travis James. Genetic analysis used for identifying the sex of eleven fish from the 2017 tagging year was provided by Drs. Brendan Wringe, Tony Kess, and Ian Bradbury. Semi-structured interviews with fish harvesters were conducted by Rachel Marshall assisted by Coline Tisserand. Interview recordings were transcribed and anonymized by Coline Tisserand and Rachel Marshall.

Publications

Chapter 2 is intended for publication in a peer-reviewed journal. Rachel Marshall performed the data analyses and wrote the manuscript and will be first author on the publication. The manuscript is co-authored with supervisors Dr. Arnault Le Bris and Dr. Jonathan Fisher, who contributed to the development of the project and reviewed manuscript drafts. Chapter 2 is also co-authored by Dr. Paul Gatti who provided geolocation analyses and comments on the manuscript. Dr. Dominique Robert is also a co-author of Chapter 2. He is the principal investigator on the NSERC Strategic Partnership Grant that funded this research, and he reviewed manuscript drafts.

Marshall, R.C., Le Bris, A., Gatti, P., Robert, D., Fisher, J.A.D., *in prep* for Journal of Animal Ecology. Reproductive behavior of Atlantic halibut interpreted from electronic tags.

Data from Chapter 2 are also included in a paper on which Rachel Marshall is co-author:

Gatti, P., Le Bris, A., Fisher, J.A.D., **Marshall, R.C.**, Robert, D., *in press.* Stock scale electronic tracking of Atlantic halibut reveals summer site fidelity and winter mixing on common spawning grounds. *ICES Journal of Marine Science*.

Chapter 3 is intended for publication in a peer-reviewed journal. Rachel Marshall conducted the interviews with fish harvesters, performed the data analyses, and wrote the manuscript. She will be first author on the publication. The manuscript is co-authored with supervisors Dr. Arnault Le Bris and Dr. Jonathan Fisher, and supervisory committee member Dr. Erin Carruthers. They each contributed to project development, provided advice on data collection operations, and reviewed manuscript drafts. Chapter 3 is also co-authored by Dr. Paul Gatti who provided geolocation analyses, data for Figure 3.2, and comments on the manuscript, and by Dr. Dominique Robert who reviewed manuscript drafts.

Marshall, R.C., Le Bris, A., Gatti, P., Carruthers, E.H., Robert, D., Fisher, J.A.D., *in prep* for Marine Policy. Combining electronic tag data and local knowledge to identify ocean management concerns.

Chapter 1: Introduction

1.1 Overview

One component of effective fisheries management is a complete and accurate understanding of the ecological requirements of the species supporting the fishery. Species' ecological characteristics include habitat preferences, seasonal migrations, and the behaviors associated with reproduction. To promote and maintain healthy populations of targeted species, these ecological needs must be understood in order to manage direct and indirect human impacts. Fishery regulations aimed at reducing direct impacts include closing areas to fishing, permanently or seasonally (Murawski et al., 2000), modifying fishing gear so that only a certain size or species is retained (DeAlteris and Reifsteck, 1993; Richards and Hendrickson, 2006), and putting limits on the amounts of target and non-target species that may be caught.

However, fisheries are not the only industries operating in the ocean. Other industries such as the oil and gas industry, aquaculture farms, marine transportation, and tourism, as well as land-based factories that discharge wastewater, may use the same environment as fisheries and may incidentally and/or indirectly impact the marine species that reside there. Incorporating spatial data of the local marine life into the spatial management of ecosystems can address these kinds of issues (Lennox et al., 2019). By integrating knowledge of the industries' established or anticipated impacts on the environment along with understanding of the spatial and temporal requirements of the living marine resources, spatial management can find a balance to maintain multiple industries alongside healthy marine populations.

Studying the ecological characteristics of marine species requires the combination of many types of data, including scientific surveys (e.g. Bell et al., 2018), aquaculture experiments (e.g. Hughes et al., 2008), and tagging studies (e.g. Kersula and Seitz, 2019). Electronic tags can record time series of physiological and environmental data in situ, which makes them increasingly capable of answering scientific questions inaccessible to conventional tagging studies or other methodologies (Hussey et al., 2015; Wilmers et al., 2015). Additionally, local knowledge from fish harvesters and other stakeholders can provide long term historical perspectives, identify local species' complexities, and contextualize other research findings (Ames, 2007; Murray et al., 2008). Electronic tagging research and fish harvesters' knowledge is rarely combined, but integrating their unique strengths has the potential to comprehensively address pressing questions for many commercially important marine species.

1.2 Electronic tagging

Tagging studies are useful in providing information on species' spatial distributions. Conventional tags only provide a tagging location and a recovery location, which, depending on the number of fish tagged, the life stages represented, and the amount of time between tag deployment and recovery, can be used to identify population level trends in residency or homing behavior, seasonal habitats, and migrations (Kersula and Seitz, 2019). Electronic tags provide the same information, but can also provide high resolution data on the individual host animal's activity between tagging and recovery (Metcalfe and Arnold, 1997) which is a major advantage over the fishery dependent mark and recapture data from conventional tagging (Bolle et al., 2005). As a result, electronic tags are becoming more and more prevalent as a tool for studying the spatial and temporal distributions of marine species (e.g. Block et al., 2001; Campana et al., 2011; Dewar et al., 2011).

Pop-up satellite archival tags (PSATs) collect high resolution (minutes to seconds) depth, water temperature, light level, and sometimes other sensor data (e.g. acceleration) over deployment periods that may span more than a year, at which point they are programmed to release from the host fish, float to the surface, and transmit data summaries to researchers via satellite (Thorstad et al., 2013). This eliminates the need to recapture the host fish in order to obtain some data (Musyl et al., 2011; Thorstad et al., 2013), although PSATs that can be physically recovered provide access to the complete high resolution data sets from which fine scale behaviors can be interpreted (Fisher et al., 2017). From PSAT time series, knowledge can be gained about species' environmental preferences, seasonal behaviors, and unique characteristics associated with spawning or feeding (Seitz et al., 2005; Aranda et al., 2013; Armsworthy et al., 2014). Geolocation models are used to infer geographic locations from environmental tag data, allowing migration paths and essential habitats to be identified (Block et al., 2001; Le Bris et al., 2018). Data from PSATs equipped with accelerometers can be used to infer activity levels indicative of specific behaviors (Nielsen et al., 2018). These data on behavior, spatial distribution, and temporal changes in spatial distribution of marine species can be used by fisheries and spatial ocean managers to maximize the efficacy of management and conservation measures (Le Bris et al., 2013; Lowerre-Barbieri et al., 2019).

1.3 Fish harvesters’ knowledge

Fish harvesters make their livelihoods targeting fish, so they are knowledgeable about aspects of species’ behavior associated with catchability such as seasonal locations, diet, and diel activity (Mackinson, 2001). From their catches, they also gain knowledge of spatial overlap between target and bycatch species (Carruthers and Neis, 2011), species size ranges in certain areas or at certain times (Duplisea, 2018), and the presence or absence of fish in spawning condition (Gerhardinger et al., 2006). This knowledge is valuable to scientific research as a way to explore species or ecosystem characteristics poorly addressed by other study methods (Berkström et al., 2019), support findings of other research and provide local details on population complexities (Murray et al., 2008; DeCelles et al., 2017), and identify discrepancies between harvesters’ observations and official reports that may require management or scientific attention (Carruthers and Neis, 2011; Duplisea, 2018). Additionally, career fish harvesters can provide knowledge of historical species’ distributions and population characteristics, and insight as to how and why they might have changed over time (Ames, 2007). Historical information from fish harvesters is especially valuable for species without robust scientific survey data outlining historical population dynamics.

Fish harvesters’ participation and knowledge is also valuable in the formulation of fisheries research objectives (Stanley and Rice, 2007; Brooks et al., 2018). The fish harvesters are active in the fishery, and fisheries management decisions impact them directly (Mackinson, 2001). Involving them in the research process allows them to highlight the research needs they identify for their industry based on their experiences

(Stanley and Rice, 2007), and have their knowledge incorporated into fisheries management (Neis et al., 1999; Mackinson, 2001) which is intended to support their industry in the long run.

1.4 Atlantic halibut

Atlantic halibut (*Hippoglossus hippoglossus*) is one of the largest flatfish species in the world. It is distributed in the North-Atlantic and Arctic oceans, and supports a number of valuable fisheries (Haug, 1990). Halibut are broadcast spawners, releasing pelagic eggs into the water column that hatch bilaterally symmetrical larvae (Haug, 1990). During metamorphosis, the left eye migrates to the right side of the head (Haug, 1990). Halibut juveniles settle on their blind side onto the seafloor in nursery grounds to assume a demersal lifestyle (Haug, 1990). Halibut spawning has been found to occur in late fall, winter, and early spring, with regionally specific peak spawning periods (Feb. to Apr. in the Gulf of St. Lawrence (Kohler, 1967), Nov. to Jan. in the southern Grand Banks, Scotian Shelf stock (Neilson et al., 1993; Armsworthy et al., 2014), Dec. to Mar. in Norwegian waters (Kjørsvik et al., 1987; Haug, 1990), and Feb. to Jun. for Icelandic caught halibut raised in aquaculture facilities under natural conditions (Björnsson et al., 1998)). Halibut have sexually dimorphic growth; they can reach lengths over two meters (Sigourney et al., 2006), and the larger, faster growing individuals are predominantly female (Haug, 1990). Females also reach maturity at larger sizes than males (Haug, 1990; Sigourney et al., 2006), female size at maturity ~103 cm, and male size at maturity ~80 cm (Sigourney et al., 2006). Adult halibut are difficult to observe in the wild because they reside in often deep water. As such, study of Atlantic halibut reproductive behavior has been limited to gonad sampling (Kohler, 1967) and aquaculture studies (e.g. Norberg et al., 2001; Brown et al., 2006), and migratory behavior has been inferred from seasonal surveys (Kohler, 1967) and conventional tagging studies (Stobo et al., 1988; Kersula and Seitz, 2019).

In 2018, Atlantic halibut constituted 27.5% of total groundfish landings value within Atlantic Canada (Government of Canada, 2020). In Canada, Atlantic halibut is currently managed as two separate stocks: the Gulf of St. Lawrence stock (NAFO divisions 4RST), and the southern Grand Banks, Scotian Shelf stock (NAFO divisions 3NOPs4VWX5Zc) (Figure 1.1). After suffering population declines in the 1990s, halibut abundances have been steadily increasing in the Canadian Atlantic, attributed in part to effective management strategies (Trzcinski and Bowen, 2016). However, while the southern stock has been extensively surveyed with a halibut-targeting longline survey and the stock status is assessed using a population dynamics assessment model (DFO, 2015), the Gulf stock currently has no assessment model (DFO, 2019a) and is poorly surveyed by the Fisheries and Oceans Canada (DFO) multispecies bottom trawl survey because adult halibut tend to outswim the research trawl (Bourdages et al., 2019; DFO, 2019a). There was no robust fishery independent index of Gulf halibut biomass until a longline survey was initiated in 2017 (DFO, 2019a).

Electronic tagging programs were implemented in 2013 using pop-up satellite archival tags to address questions of Gulf halibut spatial ecology identified by the halibut fishing industry as research needs in their region. Halibut, because of their strength and large size, are generally resistant to tagging-induced mortality or behavior-altering damage (Seitz et al., 2003). However, because there is a low halibut exploitation rate in the Gulf, low recovery of implantable data storage tags would be anticipated. Thus, PSATs, which do not necessitate recapture of the host fish for data access, are an optimal solution.

To date, analyses of Gulf halibut PSAT time series have revealed seasonal migrations from summer inshore feeding grounds to deep channels for overwintering (Le Bris et al., 2018; James et al., 2020) with Gulf-wide mixing in the winter but strong site fidelity from summer to summer (Gatti et al., *in press*), and evidence of spawning behavior during the winter inferred from unique rising behaviors present in the depth profiles (Murphy et al., 2017). New available PSATs enable a more in-depth characterization of halibut spawning behavior than has been capable in previous studies. The implications of halibut distribution and spawning behavior to ocean management can then be explored through collaboration with members of the fishing industry.

1.5 Thesis outline

The goals of this thesis are to (1) characterize halibut spawning behavior through analyses of 36 high resolution PSAT depth, temperature, and acceleration time series, and (2) use this new information concurrently with fish harvesters' knowledge to identify potential spatial conflicts between the migratory halibut population and other established and emerging Gulf industries.

The first objective is addressed in Chapter 2, which provides analyses of PSAT time series to interpret and characterize halibut spawning behavior. Spatial and temporal evidence is presented to support the interpretation of spawning rises from halibut PSAT depth time series. High resolution time series enable precise estimates of spawning times and detailed characterizations of spawning rise depths. The influence of sex, size, water temperature, and seasonal locations on variability in spawning rise characteristics is explored.

The second objective is addressed in Chapter 3. Potential user conflicts between the halibut population and human industries in the Gulf of St. Lawrence are identified through a combination of PSAT analyses and fish harvesters' knowledge research. Migration tracks modeled from PSAT time series reveal seasonal habitats, responses from industry collaborators to presentations of preliminary tagging program results identify industries with potential impact on the halibut population from spatial overlap, and reports from semi-structured interviews with halibut harvesters from the Gulf of St. Lawrence describe historical changes in halibut distribution and behavior and potential drivers of these changes.

The major findings of this thesis are summarized in the conclusion (Chapter 4) and considered in the context of current knowledge and future study of spatial management of marine species. Spawning rise depth and acceleration characterizations support further study of halibut egg and larval dispersal. Temperature effects on spawning period have implications for stock distinctions and population responses to climate change. Additionally, managers of Gulf industries, in particular the proposed

Gulf redfish fishery, need to account for the new information on halibut distribution and reproductive behavior provided in this thesis in industry planning in order to ensure the continued growth and success of the halibut population.

1.6 Figures

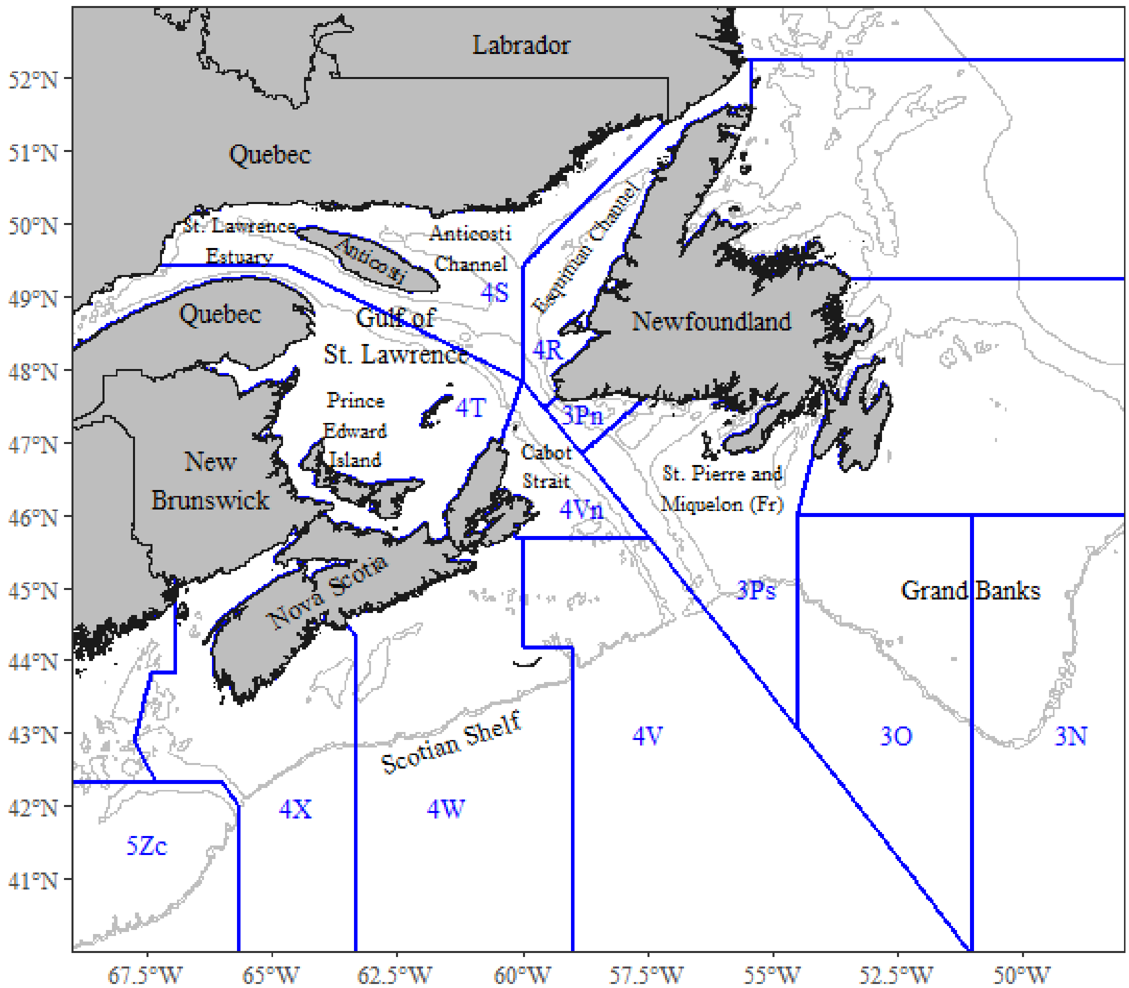

Figure 1.1: The Gulf of St. Lawrence and Atlantic Canada. NAFO divisions are shown in blue.

Chapter 2: Reproductive behavior of Atlantic halibut interpreted from electronic tags

2.1 Introduction

Effective management and conservation of commercially important marine species requires thorough understanding of the timing, locations, and behaviors of the species during spawning (Zemeckis et al., 2014). This information is useful for characterizing the structure of marine populations and defining management units (Cadrin et al., 2014). It also helps specify temporal and spatial extents of fishery closures (Le Bris et al., 2013) to minimize anthropogenic disruptions to spawning success.

While marine species display a variety of spawning behaviors, there are consistent strategies across species. Broadcast spawners release a lot of eggs at once, maximizing the chances that at least some will survive (Goldstein and Meador, 2004). Pelagic-broadcast spawners release their buoyant or semi-buoyant eggs off the seafloor into the water column where water currents and larval food availability may be optimal to support the larvae until they reach nursery grounds (Hoagstrom and Turner, 2015). Understanding where and when a species is releasing eggs can help identify essential seasonal habitats for conservation, and additional knowledge of physical oceanographic characteristics of the water column where eggs are released can assist scientists in modeling egg and larval dispersal and locating potential settlement and nursery habitats (Bradbury and Snelgrove, 2001). Batch spawning is the strategy of releasing eggs at multiple intervals over an extended period of time instead of all at once, increasing individual fecundity which would otherwise be limited by ovary size (McEvoy and

McEvoy, 1992). A batch spawning strategy also has the benefit of spreading out survival risks such as larval food availability, predation, and unfavorable oceanographic conditions in order to maximize the chance of survival for as many individuals as possible (McEvoy and McEvoy, 1992).

However, quantifying key spawning characteristics of marine fish in the wild is challenging. For many species, especially those that are migratory and reside in deep water, direct observation of spawning behavior may be impossible. Instead, many studies employ other methods such as gonad dissections, sampling of planktonic eggs, or acoustic surveys. Determining the maturity stage of fish gonads by visual inspection or histology can be used to estimate the timing and location of spawning (e.g. Kohler, 1967; McBride et al., 2013). Plankton surveys can indicate timing and spatial distribution of spawning based on presence of planktonic eggs in the survey samples (e.g. Pepin and Helbig, 1997). Acoustic studies can track fish to potential spawning grounds and identify unique vertical movement behaviors that may be associated with spawning (e.g. Rose, 1993; Grabowski et al., 2012). Additionally, laboratory tank studies can be used to reveal physiological characteristics of reproduction including egg quality, batch frequency or fecundity, and environmental effects on timing (e.g. Norberg et al., 2001; Brown et al., 2006). Tank studies can also allow for some visual observation of courting and spawning behaviors (e.g. Brawn, 1961; Smith et al., 1999), although these perspectives may be limited by the size of the tank and the fact that even the best aquaculture conditions are not the natural, dynamic ocean environment.

Electronic data storage tags are becoming more prevalent as a method for studying distinct behaviors (reproductive, migratory, feeding, etc.) in elusive marine species because of their capacity for collecting long term time series of depth use and temperature preference in the wild (e.g. Yasuda et al., 2013; Grabowski et al., 2015). Pop-up satellite archival tags (PSATs) are gaining specific popularity because they can be programed to release from their host fish, float to the surface, and transmit data via satellite. This allows high quality data summaries to be accessible to researchers independently of having to recapture the tagged fish (e.g. Block et al., 2005; Campana et al., 2011; Hussey et al., 2015). Alternatively, physical recovery of PSATs provides access to the full high resolution data sets archived on the tags (Fisher et al., 2017). Time series from electronic tags have revealed unique patterns of depth use that have been interpreted as spawning behavior (Block et al., 2001; Seitz et al., 2005; Wearmouth et al., 2013).

In the present study, high resolution data from physically recovered PSATs deployed on female and male Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence were analyzed for evidence of spawning behavior. Halibut are pelagic-broadcast batch spawners known to spawn in deep water in the winter (McCracken, 1958; Kohler, 1967). Recent studies of Atlantic halibut using PSAT data identified seasonal migrations into winter spawning grounds (Le Bris et al., 2018), and also revealed rapid ascents and descents consistent with the spawning rises described by Seitz et al. (2005) for Pacific halibut (Murphy et al., 2017). The aim of the present study was to perform in-depth characterizations of the Atlantic halibut spawning rises observed in the PSAT depth time series and test for the factors explaining the variation in timing of the spawning periods and the number of spawning rises. By providing detailed information about the spawning behaviors of Atlantic halibut, these analyses contribute to the knowledge base necessary for effective conservation and management of this population.

2.2 Methods

2.2.1 Tagging

PSAT data were collected in five tagging studies of Atlantic halibut in the Gulf of St. Lawrence between 2013 and 2017. PSATs recorded depth, temperature, and light levels in all five studies. (1) In October, 2013, twenty X-Tags (Microwave Telemetry, Columbia, Maryland, USA), recording at 2 minute intervals, were deployed in the northeast Gulf of St. Lawrence, Esquiman Channel, on halibut greater than 100 cm fork length (Murphy et al., 2017; Le Bris et al., 2018). (2) In September and October, 2014, twenty MiniPATs (Wildlife Computers, Redmond, Washington, USA), recording at 15 second intervals, were deployed in the northeast Gulf, Esquiman Channel, on potentially immature but still commercial size halibut (88-98 cm) (Murphy et al., 2017). (3) In November, 2013, and in October and November, 2014, in the southern Gulf of St. Lawrence around Prince Edward Island (PEI), five Mk-10s (Wildlife Computers, Redmond, Washington, USA), recording at 10 second intervals, and fifteen MiniPATs, recording at 15 second intervals, were deployed on potentially mature halibut greater than 130 cm (James et al., 2020). (4) In October, 2015, thirteen MiniPATs, recording at 15 second intervals, were deployed in the northeast Gulf, Esquiman Channel, on potentially mature halibut greater than 110 cm (Murphy et al., 2017). (5) In September and October, 2017, thirty-six MiniPATs, recording at 5 second intervals, were deployed Gulf-wide on potentially mature halibut greater than 130 cm. Tags deployed in 2017 were also equipped with accelerometers that recorded tag movement in three dimensions every 5 seconds.

Tagging was done exclusively aboard commercial fishing vessels using longlines with #14 or #16 circle hooks baited with cut sections of either Atlantic mackerel (*Scomber scombrus*) or Atlantic herring (*Clupea harengus*). Halibut were gently brought onboard and measured to the nearest cm (fork length). Only halibut in excellent physical condition were tagged. PSATs were tethered externally on the eyed side using a titanium sterilized dart with 180 kg test monofilament inserted between the dorsal pterygiophores following the procedures outlined by Seitz et al. (2003). Of the 109 tags deployed, 97 popped off, 64 of which were physically recovered.

Tag recoveries were conducted aboard chartered commercial fishing vessels. The Argos satellite system communicated the tag pop-off locations, which were used as search starting points. A CLS ARGOS RXG-134 goniometer (CLS America Inc., Lanham, Maryland, USA) mounted on a commercial fishing vessel was used to receive Argos pings transmitted from the PSATs within a 3 to 5 nautical mile radius. The goniometer indicated a tag's direction and relative distance from the boat, allowing tags to be tracked until they could be visually located and recovered with a dip net (Fisher et al., 2017).

Time series from recovered tags were inspected for evidence of spawning behavior. Only those fish displaying evidence of spawning behavior and for which sex could be determined were included in analyses for the present study. Of the 40 fish that displayed spawning behavior, sex could be determined for 36 (Table 2.1 and 2.2).

2.2.2 Sex determination

Sex was determined for the tagged halibut in one of three ways. (1) A veterinary ultrasound was used during tagging operations to non-invasively inspect the shape of the gonads (Loher and Stephens, 2011) for nine halibut tagged in 2014 and 2015. The veterinary ultrasound was only available during the 2014 and 2015 tagging studies. (2) Taking fin clips for genetic analysis was introduced into the tagging protocol in 2017. Genetic analysis yielded conclusive sex assignments for eleven fish displaying spawning rises on PSAT depth profiles (Einfeldt et al., *in prep*). (3) Sixteen additional halibut were assigned sex based on visual inspection of the PSAT depth profiles following the female and male patterns described by Murphy et al. (2017); females showing a very regular pattern, one clear rise every few days, over a shorter period, and males showing a greater number of rises at irregular intervals over a longer period (Figure 2.1). Depth profiles, including those with confirmed sex from ultrasound and genetics, were distributed to nine members of the research team without communicating the known sex of any profiles. By this, the twenty profiles with known sex could be used to validate the visual inspection method. Responses were reviewed, and those profiles for which there was > 75% agreement among the participants, the sex was assigned. Fish with < 75% agreement were removed from analyses. Only 2 of 20 profiles with known sex had < 75% agreement on sex assignment using the visual method, and those with > 75% agreement were assigned correctly, reinforcing confidence in the visual assignment method. The final tally of sexed halibut used for data analyses is shown in Table 2.1.

2.2.3 Spawning rise detection

Halibut spawning rises, according to the literature, have been identified as rises off of and returning to the seafloor that are extreme both in distance traveled and in rate of ascent and descent, compared to the other vertical movement events during the year (Seitz, et al., 2005; Fisher et al., 2017). Building on this idea that spawning rises are outliers in the movement of halibut, several methods were attempted to detect spawning rises throughout the time series as objectively as possible (Appendix A). A four step automated procedure using the rate of change in depth was favored after exploratory analysis. (1) Rates of depth change were estimated by calculating first order difference of the depth time series. (2) The absolute values of the rates of depth change were then filtered using a five-minute moving average to remove noise caused by tag sensor errors or random vertical movements. (3) The mean and standard deviation of the filtered time series of depth changes were then calculated. (4) Spawning events were identified as any depth change greater than the mean rate of depth change plus 12 standard deviations (an arbitrary limit selected after extensive preliminary analysis). Detected spawning rises were then confirmed for reasonable distance (i.e. ≥ 25 meters from the seafloor before returning to the seafloor based on reports of halibut spawning rise minimum depths by Armsworthy et al. (2014) and Fisher et al. (2017)) through visual inspection of the original depth time series. Also, because Atlantic halibut are known to spawn eggs in batches over a spawning period, isolated rises that did not occur in repetition with other rises were not considered to be associated with spawning a batch of eggs, and were thus excluded. Spawning rises were detected for 26 female halibut using this method.

Automated spawning rise detection was also attempted for males, but because spawning behavior of males is more random (Figure 2.1), likely due to the ability of males to spawn more readily without the physiological constraints associated with developing eggs (Coleman and Jones, 2011), the automated detection did not work. Instead, spawning rises of males were detected solely by visual inspection of the depth profiles. Any ascents reaching distances $\geq$ 25 meters from the seafloor before returning to the seafloor were considered spawning rises based on reports of halibut spawning rise minimum depths by Armsworthy et al. (2014) and Fisher et al. (2017). Isolated rises not considered to be associated with a spawning period were excluded.

2.2.4 Spawning rise characterization

To provide a complete characterization of each spawning rise, the depths and times were recorded at the start, end, and peak of every rise. Time between successive rises was calculated by subtracting the time at the peak of one spawning rise from the time at the peak of the next spawning rise. Furthermore, the effects of several environmental and individual factors on two characteristics of special interest, the date of the first spawning rise and the number of spawning rises, were evaluated using generalized linear models (GLM). GLMs were only run on the female halibut spawning rise data because of the higher confidence in the female spawning rise detection, and the understanding that females constrain reproductive potential more than males due to greater physiological requirements for producing eggs (Bateman, 1948; Coleman and Jones, 2011; McBride et al., 2015).

GLMs were run using the R statistical analysis software package “lme4”. The “lme4” package performs frequentist analyses. For exploratory and educational purposes, the GLMs were also run using the Bayesian R package “INLA” (Appendix B). The Bayesian analyses returned identical results to the frequentist analyses using “lme4”. Consequently, the present study proceeded with using the “lme4” GLM results.

The first GLM was used to analyze the variability in the date of the first spawning rise, representative of the start of the spawning season. The model tested the effect of water temperature during the season prior to the occurrence of spawning rises, fish size (cm fork length), spawning location, spawning year, and tagging location (indicative of halibut origins before the winter spawning migration) on the start of spawning. It was hypothesized that the start of a female’s spawning period occurred later following warmer water temperatures during the pre-spawning season, as found in an aquaculture study of Atlantic halibut by Brown et al. (2006). The preseason period was fixed from December 1 to January 15 in accordance with previous indications that halibut begin pre-spawning gonadal development about one to two months prior to spawning events (Haug and Gulliksen, 1988). To summarize the change in temperature during the fixed preseason, temperature was expressed in terms of growing degree days (GDD).

$$GDD = \sum_{i=1}^{n} \frac{T_{i_{max}} + T_{i_{min}}}{2} - T_0$$

Degree days were calculated using the temperature maximum (T_{max}) and minimum (T_{min}) recorded by the PSATs for each day (i) of the specified period. The reference temperature (T_0) was set at 0 °C. Spawning locations were estimated using a geolocation model that inferred daily fish position by comparing the PSAT-recorded depth data with known Gulf of St. Lawrence bathymetry (Le Bris et al., 2018; Gatti et al., *in press*). Spawning locations were categorized according to the Gulf of St. Lawrence oceanographic regions described by Galbraith et al. (2019). The GLM error was assumed to follow a normal distribution and this assumption was verified during model validation by plotting residuals versus fitted values, and versus each covariate in and not in the model (Zuur and Ieno, 2016). Model selection was implemented using the Akaike information criteria (AIC) (Akaike, 1974).

A second GLM was used to analyze the variability in number of spawning rises per individual. The model tested the effect of mean water temperature experienced by the individual during its spawning period (defined as the period between and including the dates of the first and last spawning rises), the date of the first spawning rise, fish size, spawning location, spawning year, and tagging location on the number of spawning rises. It was hypothesized that the number of spawning rises per female increased with fork length, as observed in previous studies of other groundfish (Atlantic cod: Kjesbu et al., 1996; yellowfin sole: Nichol and Acuna, 2001), and decreasing mean water temperature during the spawning period. The GLM error was assumed to follow a Poisson error distribution with a log link function, and this assumption and risk of overdispersion were verified during model validation (Zuur and Ieno, 2016). Model selection was implemented using the AIC (Akaike, 1974).

2.2.5 Acceleration

MiniPATs deployed in 2017 were equipped with three-axis accelerometer sensors. Accelerometer data were archived in the tag and were accessible from physically recovered tags. Previous studies have shown that acceleration data from externally attached PSATs can be used to infer fish activity (Nielsen et al., 2018). The present study aimed to determine whether spawning rises were associated with noticeable acceleration patterns. To do so, the magnitude of the acceleration was estimated using values from the three axes:

$$Magnitude = \sqrt{x^2 + y^2 + z^2}$$

The time series of the acceleration magnitudes for female halibut were visually inspected to quantify the frequency of spawning rises accompanied by a sudden increase in magnitude of acceleration. To further explore whether there were consistent patterns of acceleration relative to spawning rises, the maximum magnitude of acceleration between the start time and end time of each spawning rise was recorded. Acceleration magnitude in relation to male halibut spawning rises was not explored because of lower confidence in the spawning rise detection for males than for females.

2.3 Results

2.3.1 Spawning behavior characteristics

The depth profiles from 36 PSATs, 26 females and 10 males, were examined for spawning rises (Table 2.2). A total of 830 spawning rises were identified. Females exhibited between 5 and 13 spawning rises (median 7) per individual, and males exhibited between 22 and 182 spawning rises (median 57) per individual. Spawning periods for females and males overlapped (Figure 2.2). The date of the first spawning rise ranged from Jan. 7 to Feb. 26 among females and from Jan. 6 to Jan. 29 among males. Spawning period per individual lasted between 9 and 37 days (median 16 days) for females, and between 31 and 82 days (median 61 days) for males.

The spatial distribution of females and males during the period of spawning, estimated from the geolocation model, also overlapped (Figure 2.3). Grouping the locations by oceanographic region (Galbraith et al., 2019) put 4 females in the Esquiman Channel, 1 female in the Anticosti Channel, 6 females in the Northwest Gulf, 13 females in the Central Gulf, and 2 females in the Cabot Strait. One male was estimated to be in the Esquiman Channel region just on the border of the Central Gulf region, 2 males were estimated to be in the Cabot Strait region, and the other 7 males were in the Central Gulf.

Analysis of the frequency of rises occurring at each hour did not show any obvious peaks in rise frequency associated with specific light periods of the day (day, night, dawn, dusk) (Figure 2.4). Time of day of spawning rises did not differ between females and males. Spawning rises occurred between 00:11:40 and 23:57:45 (median 12:51:22) for females and between 00:03:15 and 23:55:30 (median 11:46:47) for males.

The amount of time between spawning rises was different for females and males. For females, the amount of time between rises ranged from 0.02 days to 14.8 days (median 3.15 days). For males, the amount of time between rises ranged from 0.01 days to 20.61 days (median 0.23 days) (Figure 2.5).

The durations of spawning rises from start to end were comparable for females and males. Spawning rises took between 3.25 and 201.58 minutes (median 21 min) for females, and between 3 and 237.25 minutes (median 32.12 min) for males. Out of all the female rises measured, the ascent took longer than the descent 43.9% of the time, the ascent took less time than the descent 54.4% of the time, and the ascent took the same amount of time as the descent 1.7% of the time. Out of all the male rises measured, the ascent took longer than the descent 52.2% of the time, the ascent took less time than the descent 46.9% of the time, and the ascent took the same amount of time as the descent 0.9% of the time.

The starting depths of spawning rises were comparable for females and males, with starting depths between 250 m and 503.5 m (median 396.25 m) for females, and between 278.39 m and 459.5 m (median 417 m) for males. The depths at the peaks of spawning rises were also comparable for females and males, with peak depths between 122.5 m and 472 m (median 267 m) for females, and between 144 m and 433.5 m (median 356.75 m) for males. Breakdowns of start and peak depths at spawning locations are shown in Table 2.3. Rise distances ranged from 24.54 m to 234.5 m (median 111.25 m) for females and from 24.54 m to 284 m (median 40 m) for males. The median rise distance for males is expectedly low compared to the female median because the 25-meter minimum rise distance criteria strongly influenced male spawning rise detection.

2.3.2 Effects on timing and number of spawning rises

The date of the first spawning rise was best explained by a GLM that included the effect of tagging location and preseason growing degree day (Table 2.4 and 2.5). The model predicted a significant negative relationship between the date of the first spawning rise and preseason temperature ($\beta = -5.71 \pm 2.27$, $t_{1,23} = -2.51$, $p < 0.05$), suggesting that female halibut spawn earlier when they experience warmer temperature during the pre-spawning season. The model also predicted that the spawning start date of fish tagged in Quebec occurs earlier than the spawning start date of fish tagged in Newfoundland and PEI ($\beta = -10.04 \pm 4.14$, $t_{1,23} = -2.43$, $p < 0.05$). The date of the first spawning rise was not significantly different between fish tagged in PEI and Newfoundland, although it was predicted to occur earlier for fish tagged in PEI ($\beta = -7.21 \pm 5.83$, $t_{1,23} = -1.24$, $p = 0.23$).

The number of spawning rises was found to be independent of fish size and mean temperature during the spawning period. The number of spawning rises was best explained by a GLM that included the effect of tagging location (Table 2.4 and 2.5). However, the model predicted non-significant relationships between the number of spawning rises of halibut tagged in Newfoundland and those of halibut tagged in both Quebec ($\beta = 0.23 \pm 0.17$, $z_{1,25} = 1.36$, $p = 0.17$) and PEI ($\beta = 0.21 \pm 0.20$, $z_{1,25} = 1.07$, $p = 0.28$).

2.3.3 Acceleration

Visual inspection of the magnitude of the acceleration of females showed that 97.5% (115 out of 118) of the spawning rises were accompanied with peaks in acceleration magnitude (Figure 2.6). Various spikes in acceleration magnitude were observed for each single spawning rise, but the most pronounced acceleration was often observed close to the peak of the spawning rises (Figure 2.7). Maximum acceleration during spawning rises was observed at water depths ranging from 404.5 m to 141 m, (mean = 268.79).

2.4 Discussion

Analysis of depth time series recorded by pop-up satellite archival tags deployed on Atlantic halibut revealed very unique rises (up to 284 m) off the seafloor by both females and males during the winter months. Such rises have been observed in PSAT time series for halibut species in other studies (Pacific: Seitz et al., 2005; Atlantic: Armsworthy et al., 2014; Murphy et al., 2017) and have been interpreted as spawning behavior. The characteristics of the rises analyzed in the present study support this interpretation in two ways. First, the occurrences of female and male spawning rises overlap spatially and temporally, necessities for successful fertilization of eggs. Second, female and male halibut display very different patterns in the frequency and timing of spawning rises, consistent with known Atlantic halibut reproductive physiology. Female spawning rises generally occurred at 2-4 day intervals. The same temporal pattern was observed of female Atlantic halibut in aquaculture studies of mean ovulatory rhythms

(Norberg et al., 1991) and hydration of sequential egg batches (Finn et al., 2002). This suggests that the periodic rises seen on the depth time series of females are representative of releases of batches of eggs at intervals constrained by ovulation and oocyte hydration. Additionally, studies of male halibut did not show wide fluctuations in levels of steroids associated with reproduction comparable to the fluctuations found in females (Norberg et al., 1991; Methven et al., 1992). This suggests a more continuous spawning capacity in males, which can explain the longer spawning seasons recorded for male halibut compared to females (Norberg et al., 1991; Methven et al., 1992).

Further evidence that the observed rises are spawning behavior is found in the similarities between the behavior observed on the PSAT depth time series, and that known as spawning behavior for other species. Many species of broadcast spawners, from reef fish such as grouper (Donaldson, 1995; Habrun and Sancho, 2012) to North-Atlantic groundfish such as Atlantic cod (Rose, 1993; Fudge and Rose, 2009; Grabowski et al., 2014), employ rising behavior as a spawning and egg dispersal strategy. Spawning rises have also been directly observed for several flatfish (Moyer et al., 1985; Konstantinou and Shen, 1995; Manabe et al., 2000; Manabe and Shinomiya, 2001; Carvalho et al., 2003). The frequency of species found to complete rising events as spawning behavior supports the interpretation that the rises observed of Atlantic halibut in the winter are also spawning rises.

Directly observed flatfish have been seen completing spawning rises during which one female and one male swim together up into the water column, simultaneously or sequentially release a milt cloud and eggs, and then immediately return to the seafloor

(Moyer et al., 1985; Konstantinou and Shen, 1995; Manabe et al., 2000; Manabe and Shinomiya, 2001; Carvalho et al., 2003). If halibut are performing spawning rises in pairs, the much higher number of male rises than female rises and the observation that male rises are not restricted to female egg batch intervals would support the interpretation that males are engaging in spawning rises with multiple females over the course of the spawning period. Males may also be employing alternative reproductive tactics such as attempting to “sneak in” and fertilize eggs being spawned as a result of a paired rise between a female and another male, as has been seen in other species (Bekkevold et al., 2002; Taborsky, 2008; Habrun and Sancho, 2012). It is also possible that some of the male rises seen on the time series may be part of courting behavior to attract females, as seen for the flounder *Bothus podus* (Carvalho et al., 2003).

Unlike males, females only displayed a handful of rises that occurred in close temporal proximity (< 24 hours) to each other. These might be cases where a rise was unsuccessful (i.e. eggs were not released), and so a second attempt was made. Unsuccessful rises have been reported interspersed with successful rises in directly observed spawning flatfish (Konstantinou and Shen, 1995; Carvalho et al., 2003). Alternatively, these might be cases in which the whole batch of eggs was not released during the first spawning rise, and so spawning of that batch was completed with a second rise. Konstantinou and Shen (1995) reported males almost always “checking” the abdomen of females immediately after they had spawned, and Carvalho et al. (2003) reported males frequently courting females with which they had just engaged in a spawning rise, an action which sometimes would result in another spawning rise.

The start of the spawning period was negatively correlated with water temperatures experienced during the season prior to spawning (December to mid-January). These findings suggest that warmer waters during the period of gonadal development (Haug and Gulliksen, 1988) may cause earlier spawning. This contradicts the findings of the aquaculture study by Brown et al. (2006) which found halibut spawning period to be delayed following warmer ambient conditions. However, the halibut studied by Brown et al. (2006) were kept in overall warmer water than that which was recorded by PSATs for halibut in the wild, suggesting a possible threshold of optimal water temperature for spawning. Additionally, studies of other species have found warmer water temperatures to correspond to earlier spawning times (Atlantic cod: Kjesbu, 1994; North Sea mackerel, Jansen and Gislason, 2011). In the Gulf of St. Lawrence, where the water temperature at all levels of the water column is steadily increasing (Galbraith et al., 2012; Galbraith et al., 2019), earlier spawning may result in a mismatch between when halibut larvae and their planktonic prey are in the water column (Durant et al., 2007). These findings also present water temperature as a mechanism explaining the difference in spawning periods described for different regions; Feb. to Apr. in the Gulf of St. Lawrence (Kohler, 1967), Nov. to Jan. in the southern Grand Banks, Scotian Shelf stock (Neilson et al., 1993; Armsworthy et al., 2014), Dec. to Mar. in Norwegian waters (Kjørsvik et al., 1987; Haug, 1990), and Feb. to Jun. for Icelandic caught halibut raised in aquaculture facilities under natural conditions (Björnsson et al., 1998). Genetic mixing, which may be limited when adjacent stocks have different spawning periods, could become more prevalent if regionally-ideal spawning periods shifted and overlapped as a result of warming water temperatures.

The variability in the number of spawning rises per female was assumed to reflect the number of egg batches spawned. Previous studies of groundfish spawning have found positive relationships between fish size and the number of egg batches spawned (Atlantic cod: Kjesbu et al., 1996; yellowfin sole: Nichol and Acuna, 2001). Therefore, it was unexpected that the GLM in the present study found no relationship between the number of spawning rises and fish length. However, this does not reject the idea that spawning potential increases with fish size, as higher fecundity may be expressed in other ways, such as the number of eggs per batch or egg viability, which would not be reflected in the number of spawning rises (Hixon et al., 2014). The model also found no relationship between the number of spawning rises and the mean water temperature during the spawning period. This was consistent with the report by Brown et al. (2006) which found a non-significant difference in annual spawning period length between two groups of Atlantic halibut kept at ambient and chilled water temperatures.

Previous studies of flatfish spawning have observed eggs being released at the peaks of spawning rises (Konstantinou and Shen, 1995; Carvalho et al., 2003). In the present study, bursts of acceleration were observed close to the peaks of the halibut spawning rises. These bursts, which occurred in intermediate water depths between 404.5 m and 141 m, may correspond to release of eggs. This would agree with observations from Haug et al. (1984, 1986) who found a mesopelagic distribution of Atlantic halibut eggs in Norwegian Fjords. Previous studies have proposed that the rise peak depth/egg release depth may coincide with a water current or another oceanographic characteristic that is important in egg dispersal and transport to nursery grounds (Konstantinou and Shen, 1995; Seitz et al., 2005). In the present study, water density (Appendix C) was found to be consistently lower at the peak of the spawning rises than at the starting seafloor depth. However, the differences in water density were minor (< 0.6 kg/m^3) and it is unknown how this affects egg dispersion, survival, or hatching time or success.

The findings of the present study have direct applications to Atlantic halibut fisheries management and conservation. Spawning locations and timing of halibut in the Gulf of St. Lawrence have previously been estimated based on very little data (McCracken, 1958; Kohler, 1967). While the direct for halibut fishery in the Gulf of St. Lawrence is closed during the winter, bycatch of halibut in other winter fisheries or interference with halibut spawning from other ocean users may continue. PSATs have revealed that the halibut behavior expressed during the spawning season, extensive vertical ascents into the water column, is different than their behavior during the rest of the year. Avoidance measures such as midwater trawls that may be effective during non-spawning seasons when halibut activity off the seafloor is more limited may interfere more with halibut activity during the spawning period. A comprehensive understanding of halibut spawning behavior can help managers realize these vulnerabilities and incorporate them into the conservation of the species.

2.5 Conclusion

Data from PSATs can reveal spawning behaviors of important marine species that are difficult to directly observe in the wild. The high resolution time series from recovered PSATs, similar to those from implantable data storage tags, can reveal behaviors that may be missed at the lower resolutions from satellite transmitted data sets (Fisher et al., 2017). In the present study, data sets from recovered tags were used to identify behaviors unique to the spawning period, confirm the spatial and temporal co-occurrence of females and males, provide strong evidence to support the interpretation of spawning behavior, and explore the environmental and individual factors affecting spawning characteristics. These findings demonstrate the capability of electronic tags for the study of fish spawning behavior and for providing resource managers with information useful for the maintenance of a healthy marine environment.

2.6 Tables

Table 2.1: Sex assigned to 36 halibut using one of three methods with enough confidence to include in analyses.

	Female	Male	Total
Ultrasound	4	5	9
Genetics	10	1	11
Visual Consensus	12	4	16
Total	26	10	36

Table 2.2: Metadata for the tags used in analyses. All tags used were physically recovered, giving access to the full data sets recorded on the tags. Spawning locations were estimated by the geolocation model and categorized according to the divisions of the Gulf of St. Lawrence by Galbraith et al. (2019).

Tag ID	Fork Length (cm)	Sex	Sex Assignment Method	Tagging Location	Tag Model	Tag Reso-lution	Deploy-ment Date	Pop-off Date	Days at Lib.	First Rise Date	Last Rise Date	Spawning Location
131931	108	M	Depth Profile Inspection	Newfoundland	MT X-tag	2 min	1-Oct-13	1-Oct-14	365	6-Jan	19-Feb	Esquiman Channel
131932	140	F	Depth Profile Inspection	Newfoundland	MT X-tag	2 min	1-Oct-13	24-Jul-14	296	9-Feb	25-Feb	Esquiman Channel
134684	163	F	Depth Profile Inspection	Prince Edward Island	WC Mk-10	10 sec	4-Oct-14	2-Aug-15	302	30-Jan	24-Feb	Cabot Strait
136877	88	M	Depth Profile Inspection	Newfoundland	WC MiniPAT	15 sec	27-Sep-14	28-Sep-15	366	11-Jan	26-Feb	Cabot Strait
138594	164	F	Depth Profile Inspection	Prince Edward Island	WC MiniPAT	15 sec	8-Oct-14	9-Aug-15	305	23-Feb	13-Mar	Central Gulf
138605	163	F	Depth Profile Inspection	Prince Edward Island	WC MiniPAT	15 sec	7-Oct-14	8-Aug-15	305	18-Feb	8-Mar	Cabot Strait
141661	88	M	Ultrasound	Newfoundland	WC MiniPAT	15 sec	2-Oct-14	2-Sep-15	335	21-Jan	22-Feb	Cabot Strait

Table 2.2 Continued

Tag ID	Fork Length (cm)	Sex	Sex Assignment Method	Tagging Location	Tag Model	Tag Reso-lution	Deploy-ment Date	Pop-off Date	Days at Lib.	First Rise Date	Last Rise Date	Spawning Location
141664	98	M	Depth Profile Inspection	Newfoundland	WC MiniPAT	15 sec	27-Sep-14	14-Jul-15	290	10-Jan	27-Feb	Central Gulf
141665	96	M	Ultrasound	Newfoundland	WC MiniPAT	15 sec	27-Sep-14	28-Sep-15	366	29-Jan	21-Apr	Central Gulf
141672	97	M	Ultrasound	Newfoundland	WC MiniPAT	15 sec	2-Oct-14	3-Oct-15	366	13-Jan	23-Mar	Central Gulf
141674	89	F	Depth Profile Inspection	Newfoundland	WC MiniPAT	15 sec	30-Sep-14	1-Oct-15	366	26-Jan	11-Feb	Central Gulf
150615	110	M	Ultrasound	Newfoundland	WC MiniPAT	15 sec	6-Oct-15	16-Aug-16	315	28-Jan	28-Feb	Central Gulf
150617	154	F	Ultrasound	Newfoundland	WC MiniPAT	15 sec	5-Oct-15	16-Aug-16	316	18-Feb	27-Feb	Central Gulf
150618	110	M	Ultrasound	Newfoundland	WC MiniPAT	15 sec	6-Oct-15	15-Aug-16	314	18-Jan	24-Feb	Central Gulf
150620	161	F	Ultrasound	Newfoundland	WC MiniPAT	15 sec	5-Oct-15	6-Oct-16	367	15-Feb	2-Mar	Central Gulf

Table 2.2 Continued

Tag ID	Fork Length (cm)	Sex	Sex Assignment Method	Tagging Location	Tag Model	Tag Reso-lution	Deploy-ment Date	Pop-off Date	Days at Lib.	First Rise Date	Last Rise Date	Spawning Location
152846	162	F	Ultrasound	Newfoundland	WC MiniPAT	15 sec	4-Oct-15	5-Oct-16	367	28-Jan	10-Feb	Central Gulf
152847	174	F	Ultrasound	Newfoundland	WC MiniPAT	15 sec	5-Oct-15	5-Oct-16	366	15-Jan	12-Feb	Central Gulf
172303	164	F	Genetic	Newfoundland	WC MiniPAT	5 sec	25-Sep-17	31-Aug-18	340	7-Jan	25-Jan	Central Gulf
172304	146	F	Depth Profile Inspection	Prince Edward Island	WC MiniPAT	5 sec	19-Sep-17	31-Aug-18	346	3-Feb	20-Feb	Central Gulf
172310	147	F	Genetic	Quebec	WC MiniPAT	5 sec	23-Oct-17	30-Dec-18	433	2-Feb	22-Feb	Northwest Gulf
172312	138	F	Genetic	Quebec	WC MiniPAT	5 sec	3-Oct-17	31-Aug-18	332	25-Jan	9-Feb	Central Gulf
172313	166	F	Depth Profile Inspection	Quebec	WC MiniPAT	5 sec	3-Oct-17	31-Aug-18	332	31-Jan	15-Feb	Central Gulf
172315	146	F	Depth Profile Inspection	Newfoundland	WC MiniPAT	5 sec	27-Sep-17	31-Aug-18	338	19-Feb	8-Mar	Anticosti Channel

Table 2.2 Continued

Tag ID	Fork Length (cm)	Sex	Sex Assignment Method	Tagging Location	Tag Model	Tag Reso-lution	Deploy-ment Date	Pop-off Date	Days at Lib.	First Rise Date	Last Rise Date	Spawning Location
172318	171	F	Genetic	Quebec	WC MiniPAT	5 sec	10-Oct-17	31-Aug-18	325	8-Feb	20-Feb	Northwest Gulf
172319	171	F	Depth Profile Inspection	Newfoundland	WC MiniPAT	5 sec	26-Sep-17	31-Aug-18	339	21-Feb	8-Mar	Central Gulf
172320	150	F	Genetic	Quebec	WC MiniPAT	5 sec	23-Oct-17	10-Apr-18	169	17-Jan	2-Feb	Northwest Gulf
172321	155	F	Depth Profile Inspection	Newfoundland	WC MiniPAT	5 sec	25-Sep-17	31-Aug-18	340	8-Feb	19-Feb	Esquiman Channel
172323	180	F	Genetic	Quebec	WC MiniPAT	5 sec	23-Oct-17	31-Aug-18	312	6-Feb	22-Feb	Northwest Gulf
172324	160	F	Genetic	Newfoundland	WC MiniPAT	5 sec	25-Sep-17	31-Aug-18	340	4-Feb	19-Feb	Esquiman Channel
172327	146	F	Genetic	Newfoundland	WC MiniPAT	5 sec	27-Sep-17	31-Aug-18	338	26-Feb	10-Mar	Esquiman Channel
172329	143	F	Genetic	Quebec	WC MiniPAT	5 sec	23-Oct-17	31-Aug-18	312	18-Feb	27-Mar	Northwest Gulf

Table 2.2 Continued

Tag ID	Fork Length (cm)	Sex	Sex Assignment Method	Tagging Location	Tag Model	Tag Reso-lution	Deploy-ment Date	Pop-off Date	Days at Lib.	First Rise Date	Last Rise Date	Spawning Location
172333	135	M	Genetic	Quebec	WC MiniPAT	5 sec	3-Oct-17	31-Aug-18	332	14-Jan	1-Mar	Central Gulf
172336	130	F	Depth Profile Inspection	Newfoundland	WC MiniPAT	5 sec	27-Sep-17	21-Jul-18	297	5-Feb	18-Feb	Central Gulf
172337	139	M	Depth Profile Inspection	Quebec	WC MiniPAT	5 sec	3-Oct-17	31-Aug-18	332	17-Jan	19-Mar	Central Gulf
172338	165	F	Genetic	Quebec	WC MiniPAT	5 sec	3-Oct-17	31-Aug-18	332	30-Jan	14-Feb	Central Gulf
172342	202	F	Depth Profile Inspection	Prince Edward Island	WC MiniPAT	5 sec	23-Sep-17	31-Aug-18	342	16-Feb	7-Mar	Central Gulf

Table 2.3: Spawning rise depth use by female and male halibut at each spawning location.

Sex	Spawning Location	Fish Count	Maximum		Minimum		Mean	
			Start Depth	Peak Depth	Start Depth	Peak Depth	Start Depth	Peak Depth
Female	Anticosti Channel	1	326	213	250	153.5	295.1	185.1
	Cabot Strait	2	503.5	472	476.5	279.5	490.7	386.2
	Central Gulf	13	482.5	403.5	303.5	158.5	407	274.5
	Esquiman Channel	4	376.5	289.5	253.5	151	299.9	223.6
	Northwest Gulf	6	421.5	333	251.5	122.5	361.3	256.7
Male	Anticosti Channel	0	--	--	--	--	--	--
	Cabot Strait	2	449	421.5	328	259	422.8	371.4
	Central Gulf	7	459.5	433.5	283	144	412.3	353.4
	Esquiman Channel	1	329.8	293.2	278.4	168.1	308.1	265.4
	Northwest Gulf	0	--	--	--	--	--	--

Table 2.4: Generalized linear model selection using the AIC scores. Continuous covariates include fork length (FL), preseason growing degree day (GDD), first spawning rise date (FRD), and spawning period mean temperature (TMP). Categorical covariates include spawning location (SL), spawning year (SY), and tagging location (TL).

GLM	Response Variable	Error Distribution	Fixed Effects		AIC	r^2
1	Date of First Spawning Rise	Gaussian	Full Model	FL+GDD+SL+SY+TL	186.49	0.56
			Covariates of Interest	GDD	180.81	0.19
			Selected Model	GDD+TL	178.46	0.38
2	Number of Spawning Rises	Poisson	Full Model	FL+FRD+TMP+SL+SY+TL	131.76	0.44
			Covariates of Interest	FL+TMP	118.55	0.02
			Selected Model	TL	116.61	0.13

Table 2.5: Generalized linear model parameter estimates.

GLM	Response Variable	Covariate	Estimate	SE	2.5%	97.5%
1	Date of First Spawning Rise	Preseason GDD	-5.705	2.274	-10.161	-1.249
		Tagging Location				
		Newfoundland	Baseline (0)	--	--	--
		Prince Edward Island	-7.206	5.829	-18.630	4.218
		Quebec	-10.044	4.138	-18.156	-9.933
2	Number of Spawning Rises	Tagging Location				
		Newfoundland	Baseline (0)	--	--	--
		Prince Edward Island	0.211	0.197	-0.185	0.590
		Quebec	0.231	0.169	-0.104	0.561

2.7 Figures

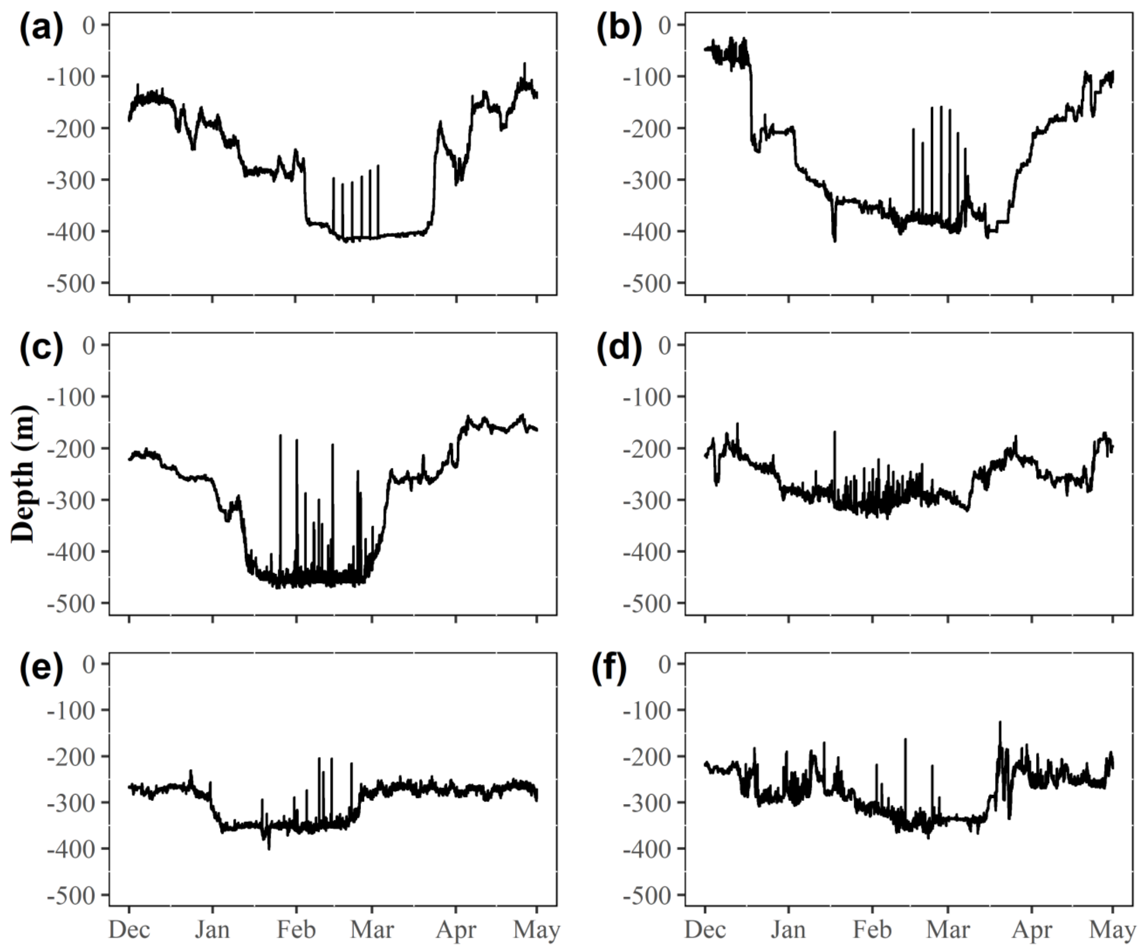

Figure 2.1: Examples of depth profiles showing the presumed spawning behavior of (a) a known female halibut showing spawning rises at a very regular interval pattern, (b) a halibut inferred to be female by visual inspection of the depth profile and comparison to the depth profiles of known females, (c) a known male halibut showing a greater number of rises than the females and at much more irregular intervals, (d) a halibut inferred to be male by visual inspection of the depth profile and comparison to the depth profiles of known males, and (e and f) two examples of halibut showing presumed spawning behavior for which sex could not be conclusively determined.

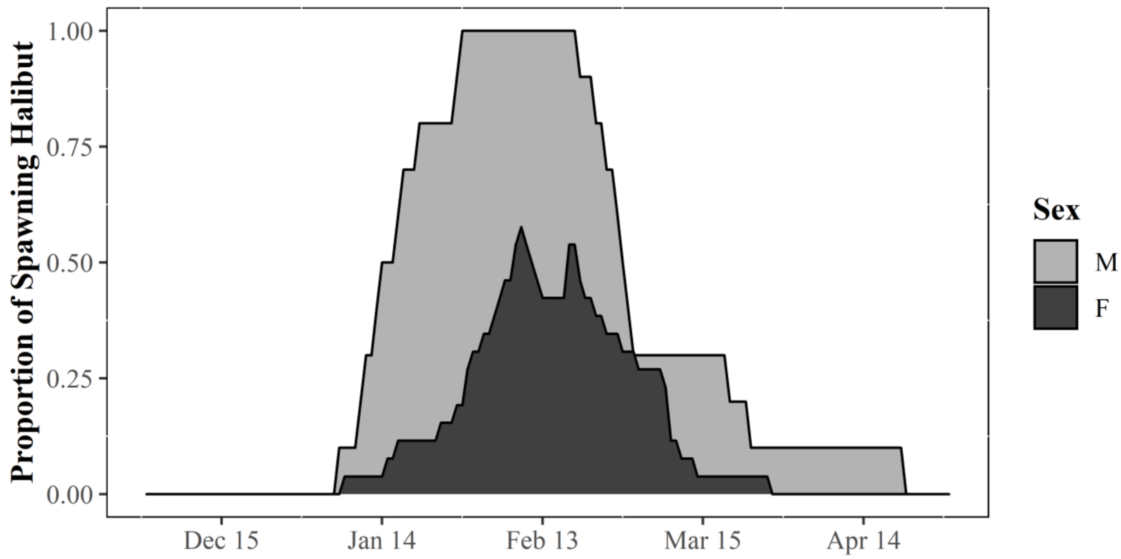

Figure 2.2: Proportion of halibut across all tagging years, grouped by sex, considered to be within their spawning period on a given day. Only halibut exhibiting spawning behavior were included in this analysis. Spawning periods were defined as the period between and including the first spawning rise and last spawning rise for each individual.

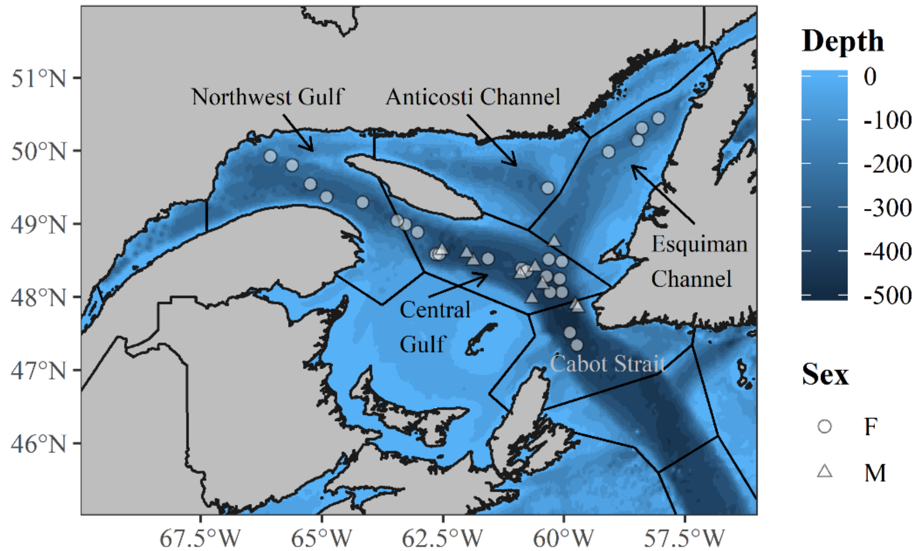

Figure 2.3: Estimated mean location of individual halibut during the period of spawning rises. The black lines delineate the oceanographic regions of the Gulf of St. Lawrence as defined by Galbraith et al. (2019). Halibut remained in their general spawning areas for several months (Gatti et al., *in press*).

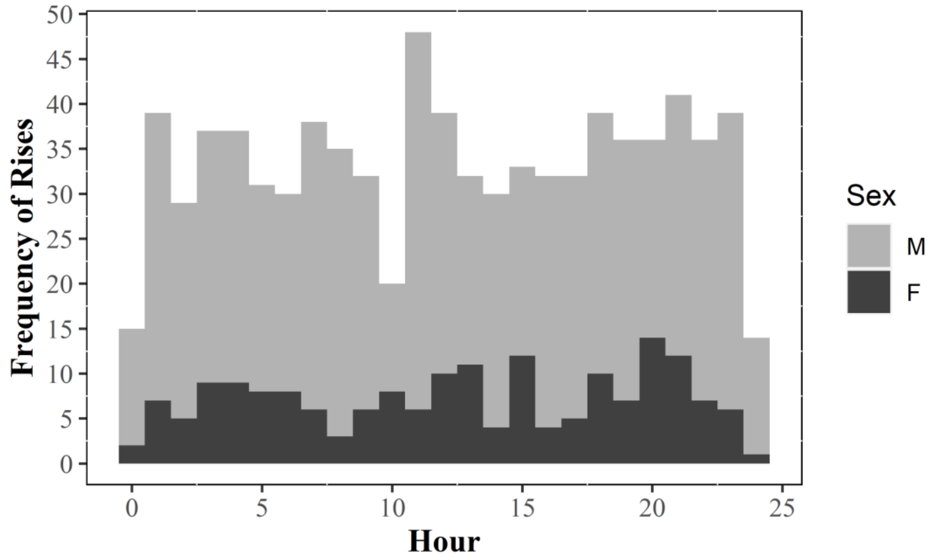

Figure 2.4: Frequency of female and male spawning rises per hour of the day.

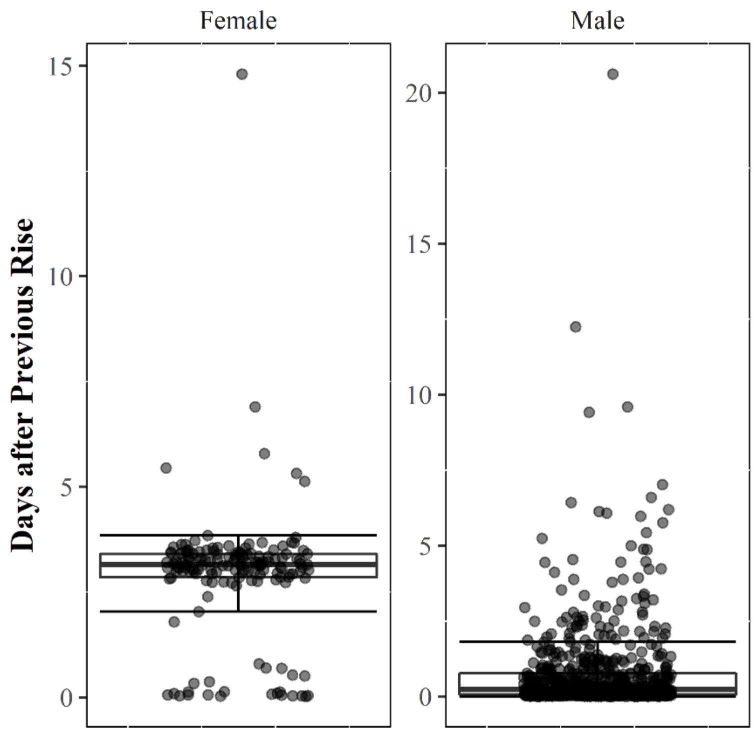

Figure 2.5: Number of days between successive spawning rises. Boxplots show data medians and first and third quartiles, and whiskers extend to the last values ≤ 1.5 times the interquartile range.

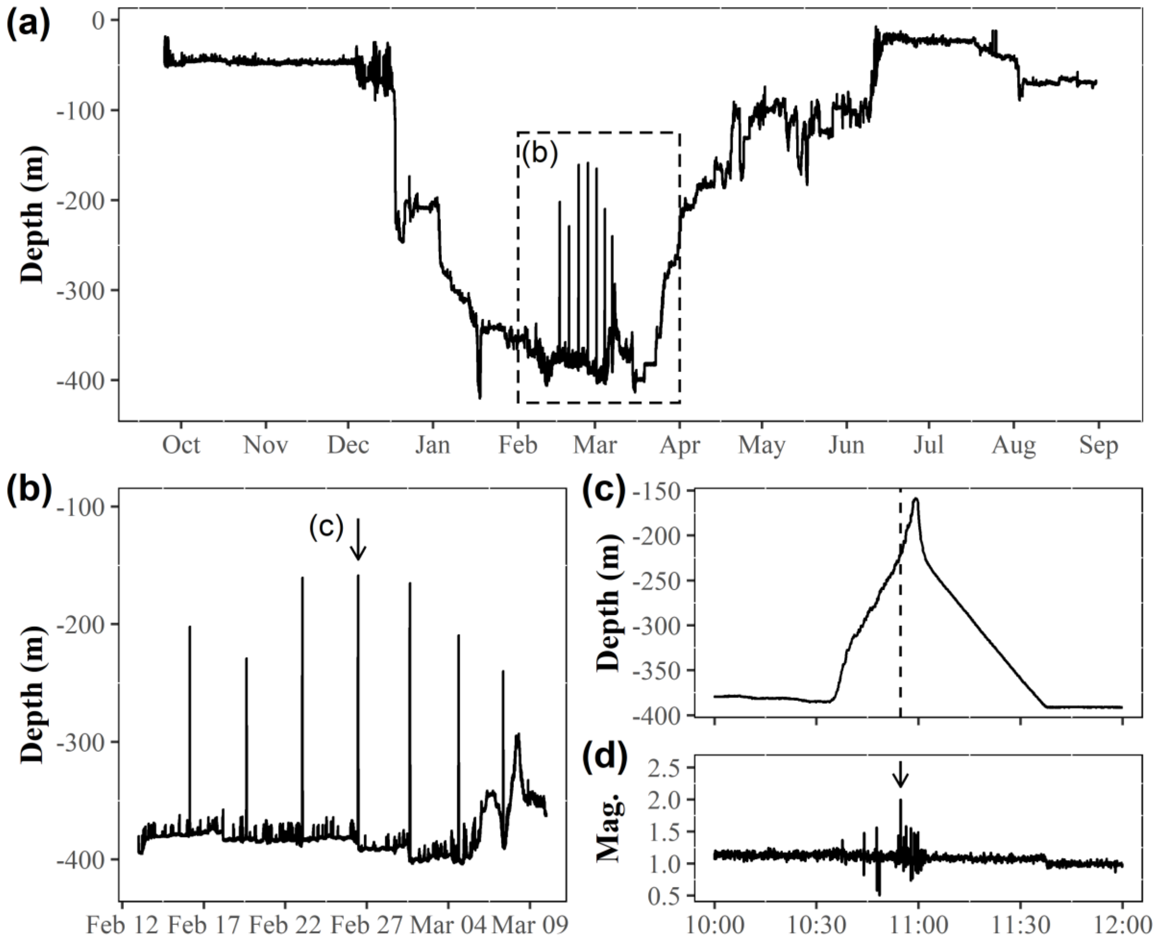

Figure 2.6: An example of detailed spawning rise observations for one female halibut. (a) The full depth profile recorded by the electronic tag. (b) A close look at the depth profile during the winter spawning period showing seven clear spawning rises. (c) The depth profile for a single spawning rise, showing a vertical ascent and descent of 227 meters over the course of an hour. (d) Magnitude of the acceleration revealing a burst right before the peak of the spawning rise.

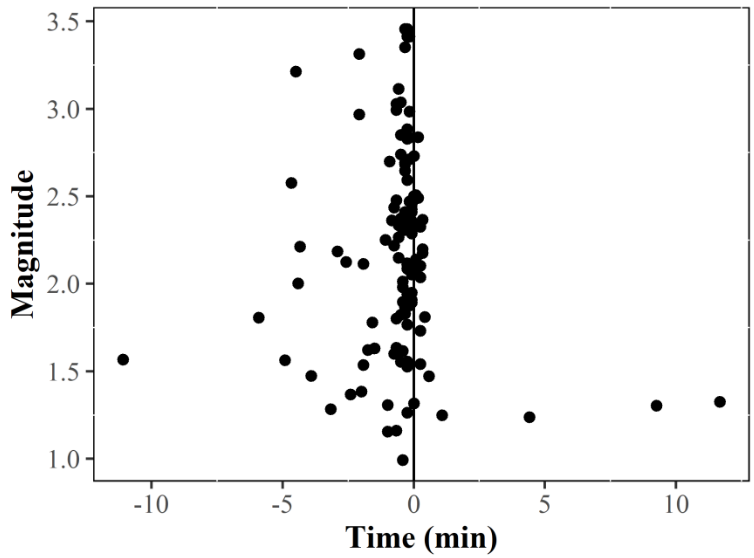

Figure 2.7: Time between the maximum acceleration values observed during a female spawning rise and the peak of the spawning rise (n = 118) as a function of acceleration magnitude. Negative times indicate when the maximum acceleration occurred before the peak of the spawning rise.

Chapter 3: Combining electronic tag data and fish harvesters' knowledge to identify ocean management concerns

3.1 Introduction

When managing the human uses of a marine ecosystem, understanding the behaviors, spatial distributions, and timing of critical life-stage characteristics of the species inhabiting the ecosystem is crucial to maintaining ecosystem structure and function and preventing damage from human uses. This is especially relevant in systems where multiple human uses of the marine environment overlap in space and time with conflicting interests and cumulative impacts (Katsanevakis et al., 2011). Therefore, integrating knowledge of the vulnerabilities and needs of the species into resource management in the context of spatial overlap of multiple industries is required for maintaining a functioning marine ecosystem.

Use of electronic tags has rapidly emerged as a method to facilitate development and testing of hypotheses relevant to spatial analyses of marine species (Hussey et al., 2015). The spatial and temporal data they record can be used to address questions of essential habitats, migration paths, and environmental preferences, directly relevant to conservation and management (Lennox et al., 2019). Electronic tags can also be used to demonstrate spatial aspects of species' responses to environmental change (Hazen et al., 2018; Lowerre-Barbieri et al., 2019) such as reductions in habitat range or poleward shifts in distribution caused by rising water temperatures (Hazen et al., 2013). However, electronic tags have limitations: (1) battery life restricts the data collection frequency and duration, (2) cost limits the number of tags that can be deployed in a study, and (3) recoverability controls the number of tags that can be analyzed. Accounting for these limitations in study design and incorporating complementary data sources to meet research objectives can maximize the value of electronic tagging data.

Fish harvesters' knowledge (FHK) is another research approach that can provide insight over long observation periods into species' ecological characteristics that may not be well addressed by other study methods (Neis et al., 1999). Lifetime fish harvesters may have decades of knowledge on the fish species that they target. They make their livelihoods out of finding and catching possibly hundreds of fish a day during a fishing season, and to do that, they need to be familiar with the distribution and behaviors of the species they target. They can contribute data beyond a traditional study method's technical capacity (Berkström et al., 2019) and fill gaps in historical data (Ames, 2007), they can support and expand on parallel studies (Murray et al., 2008; Decelles et al., 2018), and they can reveal discrepancies between their understandings and official reports that may be affecting the efficiency of management or conservation measures (Carruthers and Neis, 2011; Duplisea, 2018). Fish harvesters are also familiar with the different fisheries and other industries using the ecosystem, and thus can identify potential overlaps and associated impacts.

The Gulf of St. Lawrence (hereafter, the Gulf) is one environment that could benefit from including fish harvesters' knowledge into ecosystem management. The Gulf supports many industries, including multiple fisheries. Fish harvesters' knowledge of overlaps between industrial activities and distributions of commercially targeted species could be applied to the management of those industries. Additionally, harvesters' knowledge of the history of species' distributions, how they have changed over time, and reasons for the changes are useful for future management of the marine resources in a dynamic environment. The Gulf of St. Lawrence has undergone documented changes in the past decades in physical oceanography, species diversity and abundances, and fishing practices. Water temperatures have been steadily increasing at all levels of the water column (Galbraith et al., 2012; Galbraith et al., 2019). With the collapse of the groundfish in the 1990s came changes to fishing regulations such as a moratorium on Atlantic cod trawling in the Gulf (Brassard et al., 2020) and the introduction of several exploratory fisheries (e.g. Atlantic hagfish: DFO, 2017a; sea cucumber: DFO, 2017b). In the past few decades, some local species have been seen in increasing abundances, including those that had previously been in great decline. Mean catch per unit effort (CPUE) of American lobster (*Homarus americanus*) in the west coast region of Newfoundland more than doubled from 2004 to 2015 (DFO, 2016). Biomass estimates of both northern shrimp (*Pandalus borealis*) (DFO, 2020a) and turbot (*Reinhardtius hippoglossoides*) (DFO, 2019b) showed steady increases between 1992 and 2003 before starting to decline. Redfish (*Sebastes mentella* and *S. fasciatus*) biomass estimates have been increasing since 2017 following the recruitment events of 2011, 2012, and 2013, the most abundant cohorts recorded by the Fisheries and Oceans Canada (DFO) research survey which has been operating since 1984 (DFO, 2020b).

The Atlantic halibut (*Hippoglossus hippoglossus*) population in the Gulf has also been growing, as evidenced by greater landings (nearly 1,300 tons in 2018 up from 91 tons in 1982), and higher abundances of small halibut in the DFO multispecies bottom trawl surveys (Bourdages et al., 2019; DFO, 2019a). However, management of Gulf halibut remains based on limited ecological and historical data. The DFO multispecies bottom trawl surveys do not effectively sample adult halibut which can outswim the trawls (Trzcinski and Bowen, 2016; Fisher et al., 2017), and not until 2017 was a dedicated halibut longline survey implemented in the Gulf of St. Lawrence to improve the survey basis for halibut stock assessment by sampling the mature halibut using the preferred gear of the commercial fishery (DFO, 2019a). Recent findings from electronic tag studies of Gulf halibut are revealing much about their distribution and spawning behavior (Murphy et al., 2017; Le Bris et al., 2018; James et al., 2020; Gatti et al., *in press*; this thesis, Chapter 2), but drivers of recent changes in abundance and distribution, and potential impacts to the population from future ecosystem changes are still largely unaddressed.

To explore those knowledge gaps, this project incorporates results from both electronic tag studies and FHK interviews. Halibut migration and spawning behaviors, historical changes to population distribution and abundance, and potential spatial and temporal overlaps between the Atlantic halibut population and other industries in the Gulf (i.e. trawl fisheries, oil exploration, and effluent discharge) are identified, providing relevant information that managers can use to mitigate user conflicts that could impact Atlantic halibut productivity.

3.2 Methods

3.2.1 Electronic tagging

Pop-up satellite archival tags (PSATs) are electronic tags that record depth, temperature, and light levels, and can be programmed to pop off from their host fish at a specific time (Musyl et al., 2011). After popping off and floating to the surface, they transmit an hourly to daily summary of their collected data to researchers via satellite. In contrast to the low resolution transmitted data, high resolution (minutes to seconds) raw data time series are available from PSATs that can be physically recovered after pop-off. These time series can be used to estimate the horizontal movement of the host fish using a geolocation model (Le Bris et al., 2018).

Between 2013 and 2018, 109 PSATs were deployed on legal size Atlantic halibut (> 85 cm) in the Gulf of St. Lawrence (NAFO divisions 4RST). Using methods to intercept PSAT transmissions to satellite (Fisher et al., 2017), 62 PSATs were physically recovered and used for analyses. All tagging and recovery was done aboard commercial fish harvester vessels (n > 15) privately chartered or as part of collaborative surveys with DFO, the fishing industry, and academic partners. The analyses of tagging data revealed halibut annual migration patterns and spawning behaviors, information previously largely unknown on which industry representatives had requested study during the early stages of project development. A geolocation model inferred daily fish position by comparing the PSAT-recorded depth data with known Gulf of St. Lawrence bathymetry to estimate locations and migrations of the halibut during the tag deployment period (Le Bris et al., 2018; Gatti et al., *in press*). Spawning behavior was identified from the presence of spawning rises (this thesis, Chapter 2).

3.2.2 Presentations of electronic tagging results

To inform stakeholders and managers of research progress and to gain their perspectives on the results, preliminary findings of halibut migrations and spawning behavior (including data and results from Murphy et al., 2017; Le Bris et al., 2018; James et al., 2020) were presented at several meetings, including two halibut stock assessment meetings with DFO (Mont-Joli, Quebec, 2017 and 2019) at which were present scientists, managers, and fishing industry representatives. These results were also presented at annual general meetings of fishing associations including the Prince Edward Island Fishermen's Association (PEIFA) (2019 and 2020), and L'association des Capitaines-Propriétaires de la Gaspésie (ACPG) (2019). Additionally, these results were presented during thirteen public meetings with Fish, Food, and Allied Workers Union (FFAW) members in western Newfoundland and Labrador (Jan., Apr., and May, 2019) (Figure 3.1). Approximately 230 halibut harvesters, some of whom who had been involved in the project since its early stages, attended the public meetings in Newfoundland and Labrador.

3.2.3 Semi-structured interviews

Over the course of the PSAT tagging project, during personal communications between researchers and industry collaborators, harvesters described their observations of halibut abundance, movement, and behaviors. To more formally integrate this fish harvesters' knowledge into the study, private semi-structured interviews were arranged and conducted regarding the Gulf of St. Lawrence Atlantic halibut and its fishery. Interviews were conducted with a total of seventeen participants based on the west coast of Newfoundland (Figure 3.1). All participants were groundfish harvesters (16 captains, 1 crew member) with at least five years of experience fishing for Atlantic halibut in the Gulf of St. Lawrence. Participation was voluntary, and every participant signed a consent form approved by the Memorial University of Newfoundland ethics board (ICEHR#: 20192281-MI (Appendix D)) confirming that participants' private information would not be disclosed, and that participants had granted permission for publication of their interview responses.

Because some of the interview questions were related to information being presented at the public meetings with Newfoundland and Labrador fish harvesters in January, 2019, effort was made to hold interviews with harvesters before they heard the meeting presentations. However, an email sent to fixed gear harvesters on the west coast of Newfoundland through the FFAW list serve inviting harvesters to contact researchers and participate in interviews only yielded two interview appointments. Because travel logistics necessitated that interviews be conducted during the same tour as the public meetings in January, 2019, further recruitment of harvesters to interview before meetings proved impossible. The majority of interviews occurred immediately following public meetings with harvesters who had volunteered after a call for participants at the end of the meeting presentations. To increase the number of participants, an additional round of interviews was conducted in February, 2020, during which five more interviews were arranged following personal communications with harvesters for whom contact information was publicly available.

Participants were all interviewed privately except in one instance in February, 2020 when a captain and a member of his crew were interviewed jointly. Average interview duration was 25 minutes, but interviews ranged from 6.5 to 65 minutes long. Questioning followed an interview guide (Appendix E) that focused on how the halibut fishery has changed over time, general understanding of halibut distribution, biology, and ecology, and the vulnerability of the halibut population to other industries in the Gulf of St. Lawrence. Some interview questions expanded beyond the goals of the present study; responses to those questions were summarized separately (Appendix F). Because the interviews were semi-structured, harvesters could elaborate beyond the bounds of the questions as they saw fit in order to effectively communicate their experience in the fishery and with the species. No more than two researchers were present during interviews, all of which were audio-recorded. After all interviews were completed, recordings were transcribed and reviewed by the same researchers that conducted them in order to limit the number of people handling participants' personal information. Transcriptions were anonymized, each participant was assigned a unique identification number (e.g. 523), and responses were summarized to identify common themes.

3.3 Results

3.3.1 Electronic tagging

Halibut were tagged between September and November in waters between 15 and 300 meters deep. Depth time series recorded by PSATs showed that regardless of tagging location, the halibut consistently occupied depths between 200 and 500 meters between January and April. In summer, halibut were distributed in two depth ranges: some halibut migrated into coastal shallow waters (~50 m), while others remained offshore (~200 m). Reconstruction of fish migration tracks showed strong evidence of site fidelity, with many halibut returning to the same areas where they were tagged after wintering in deep waters (Gatti et al., *in press*). Spawning rises, which occurred between January and late April, were located in the deepest channels of the Gulf of St. Lawrence with a high concentration at the intersection of the Laurentian and Esquiman Channels (Figure 3.2). Spawning rises ranged from 24.54 m to 284 m (mean 68.95 m) in distance from the seafloor. Seafloor depths were between 250 m and 503.5 m (mean 400.2 m), and spawning rises reached depths between 472 m and 122 m (mean 331.3 m). Each rise lasted between 3 and 237.25 minutes (mean 38.08 minutes) from leaving the seafloor to returning to the seafloor.

3.3.2 Meeting responses identifying spatial issues

The halibut harvesters interviewed following presentations of PSAT preliminary results depicting halibut migrations and presumed spawning behaviors identified three emerging industries with the potential for spatial overlap with Atlantic halibut in the Gulf of St. Lawrence (Figure 3.2). At 4 of the 13 public meetings with halibut harvesters on the west coast of Newfoundland in 2019, harvesters in attendance raised the subject of the exploratory winter redfish fishery in the deep channels of the Gulf overlapping with the halibut winter migrations and spawning locations modeled from the PSAT data. The redfish fishery being explored would occupy the same grounds as the historical redfish fishery in the central channels of the Gulf (Gascon, 2003; Senay et al., 2019) (Figure 3.2). At one public meeting, the point was also raised that data on halibut spawning locations had not been included in the last environmental impact assessment for the oil drilling project "Old Harry", which had been planned for an area in the Gulf overlapping with the geolocated halibut spawning areas presented at the meeting (Figure 3.2). Additionally, at a stock assessment meeting, following the presentation of tagging results, a fishing industry representative highlighted the potential for spatial overlap between halibut summer migrations into the southern Gulf and the proposed location for effluent discharge into the Northumberland Strait between Prince Edward Island (PEI) and Nova Scotia from the Nova Scotia based paper pulp mill, Northern Pulp (Figure 3.2) (Northern Pulp, 2019a, 2019b). After spatial management issues were raised at multiple public meetings, the question of relationships between Gulf halibut and other industries was incorporated into the FHK interview guide to quantify harvesters' perspectives.

3.3.3 Fish harvesters' knowledge

The seventeen fish harvesters who participated in semi-structured interviews were all longline harvesters (20-55 ft boats) who had worked in the fishing industry for between 6 and 47 years (median 35 years). They had between 6 and 30 years of experience targeting halibut in the Gulf of St. Lawrence. All the harvesters at the time of the interviews held multiple licenses, although 5 harvesters reported that early in their careers (~30 years previous), halibut was their only fishery. Licenses held varied by individual, and could include pelagic species (herring, mackerel) or invertebrates (lobster, crab, etc.) in addition to the other species included in their groundfish license besides halibut (cod, turbot, etc.). Having multiple licenses was an indication that the interviewed harvesters had experience on the water for more time out of the year than the direct for halibut fishing season (select weeks between April and October in NAFO divisions 4R and 3Pn (Pinkerton et al., 2018)). Consequently, their knowledge of halibut distribution and behavior in the Gulf might not be limited to the halibut season and could include knowledge gained from seeing halibut as bycatch in other fisheries. Additionally, four harvesters mentioned that they had worked on halibut scientific surveys which are broadly distributed due to a stratified-random design, and which are scheduled independently of the direct for halibut fishing period.

Fish harvester reports of fishing depths during the halibut fishing season ranged from < 5 fathoms (< 10 m), to 250 fathoms (> 450 m). Five harvesters specifically noted the wide distribution during the fishing season, claiming that they could find halibut at any depth during the halibut fishing season, as one harvester put it, “so shallow as two fathom, a fathom, out so deep as 250 fathom.” (523). In addition, all the harvesters also recognized an increase in halibut abundance in the Gulf of St. Lawrence over the past few decades based on notable changes in the frequency of halibut bycatch in other fisheries and overall halibut catch rates in direct for halibut fishing operations. Those who had fished exclusively for halibut early in their careers could provide comparative examples of how they have seen the abundance increase in terms of catch (1000 lbs) per tub of gear (the number of tubs can be used to estimate fishing effort, each tub holding approximately 100 hooks):

> Now we're only out for a few hours, we only got 1000 pounds to catch, […] The last years that we were fishing halibut [traditionally, before the steady increases in overall quota], […] we were fishing 80 [tubs of gear], and if we got 5 or 6 thousand pounds out of a week, it was good. Now if we're fishing 6 tubs, we probably get two quotas, 2000, 3000 pounds with six tubs. That's how plentiful they got. (283)

> First if you had got 500 pound a day, you was doing good, that was forty tubs of gear, too. […] You catch that much on a tub now. (882)

> Usually we'd be there for a week, set up two, up to two hundred and some odd tubs of gear, in one week and we'd be lucky, like you'd be gone the whole week and you come back with three or four thousand pounds of fish you thought you were doing good, for a whole week's fishing. So you know, that's totally different from now, right? You don't have to go very far, just go off home and get it. (181)

By these estimates, CPUE went from between 56.7 and 283.5 kg/1000 hooks to between 1,512 and 2,268 kg/1000 hooks (DFO measures CPUE for longline-caught halibut in kg per 1000 hooks) over the decades of the fish harvesters' careers. Harvesters put forward three explanations for the increase in halibut abundance: (1) the moratorium on groundfish trawling (10 reports):

> Well, I'll tell you, halibut started coming back after the moratorium when they gave up dragging for groundfish, in the northern Gulf of St Lawrence. And, since then our halibut stocks have just exploded. (662)

> Before the moratorium was called, […] where we were traditionally fishing cod and halibut, the draggers were there. […] You could talk to anybody that's on a

> dragger, a 45 to a 65-foot dragger, and they'll tell you that almost any given time around the summer months, […] on every tow, […] anywhere from 35 to 40, to 50, small to market to large halibut. […] They were allowed to keep them, back, say, before the moratorium. So now, if you're not allowed to keep them, they're going back over, they're reproducing. […] So my opinion, they're just not being kept, and because they're getting put back in the water, they're reproducing, and it's a cycle. (332)

(2) the implementation of the Nordmore grate in otter trawls (7 reports):

> Ever since the Nordmore grate in the draggers, that's gonna explode it, because they are not catching no bycatch, everything is going back you know, going on through the grate. One time when the draggers came in they always had halibut and never, not anymore, right? We think that’s what solved the halibut fishery here in the Gulf. (184)

> And then the halibut started coming back. I guess the big part of the reason why, […] the draggers in the Gulf […] they just dragged it all, all these little halibut, three or four, five inches long. And since they changed the net […] to put the Nordmore Grate in, all they’re catching is what they’re supposed to catch, they’re not catching all the little fish […] and all that stuff, they’re growing now, right? That's the reason [halibut] has exploded in the Gulf; there’s none being caught. (442)

> Well I think, I think what happened was the Nordmore grate. When they invented the Nordmore grate and started to use it in the shrimp fishery, in the otter trawl fishery, […] everything started to come back. Prior to that […] they were catching, they weren't targeting them, but them fish were there. Whereas now, I mean they're all going through the grate and so then they got a chance to grow, right. So it’s the Nordmore grate, I believe, Nordmore grate is the reason for, or one of the main reasons for the explosion in the population. (291)

and (3) warming waters due to climate change causing species that had occupied more southern ranges to move north (3 reports):

> The migration, the same as everything else, I think. […] So that's water temperature, right? And when it comes to the halibut, it was always out there somewhere, […] whether it was on the Grands Banks, or down in [NAFO division] 3NO, migrate up across more because of the water temperature. (523)

> The climate change too has a lot to do with it, just like the lobster, right? […] Migrations, everything is moving north, everything is, […] you're seeing these things more in the Gulf than you've never seen before. And plus besides the grate system, right? But everything is moving. […] That's what's happening. (181)

Having reported that bycatch of small halibut in trawl fisheries was a main contributor to the low halibut abundances in the past (i.e. groundfish trawling and shrimp trawling without the Nordmore grate), the harvesters similarly expressed concern that reintroduction of redfish trawling in the deep channels of the Gulf of St. Lawrence would cause halibut abundance to fall again, especially as halibut have been found to be overwintering in those deep channels at the time when redfish trawling would be taking place. This issue was raised at public meetings in 2019, and then emphasized by the six harvesters interviewed in 2020:

> That redfish fishery. […] That better be watched close I tell you. Observer aboard them boats. The redfish fisheries, that's gonna ruin halibut. You gonna see halibut go down when that comes in full swing. (353)

> I am sure that when they drag for redfish, they're gonna be dragging in deep water. […] So I am concerned that, in the winter time, they'll, based on the science that they said they've done now, so that they said the fish [halibut] go here in the winter time to spawn […] So they're gonna be dragging and they're gonna impact halibut when they are in a spawning mode. […] We've been in basically, conservation mode for years and years, […] increasing the measure, making sure that they come back, and so we don't want them to be destroyed in a few years when they are in their spawning stage. But that's what gonna make the most impact if you take them in the spawning stage. Any other time of the year wouldn't be probably so, wouldn't be so bad. (283)

Some harvesters also mentioned halibut bycatch in the turbot gillnet fishery as another potential impact on halibut abundance:

> If they get rid of the gillnets, how thick would [the halibut] be? Turbot nets, I mean. Lot caught up in that. (882)

> You got the turbot fishery that’s going on in the Gulf with those gillnets, how much are they destroying? […] Because anything in the net is dead. (523)

All harvesters who were interviewed after having heard the public meeting presentations were in agreement with the findings presented that halibut migrate to deeper water in the winter. Of those that were interviewed prior to meetings, one did not know if halibut migrated, and the other reported winter halibut migrations to deep water, consistent with the findings from the tagging study:

> Halibut is usually in the shallow water in the spring of the year and coming on the summer, they usually hang around shallow water, and then in the Fall of the year they migrate more to the deep. (181)

However, three harvesters specifically expressed the opinion that while many of the halibut were returning inshore in the summer, there remained a number of them that stayed deep:

> We basically fished offshore. […] Them halibut are still around there, plus there is fish inshore so they are basically, we are seeing fish all over the ground, […] I don't know if there is stock or a different stock or a different bunch of fish off shore that’s not being fished. I don't know if that's what. (283)

> Those fish [offshore in July, seen as bycatch in the turbot fishery and as target catch in early years of fishing halibut], I assume, I would think that they don't come in out of that in the summertime. […] I would suspect that they’d probably stay out there. (772)

> [In the summer] they go right in to the beach, or you stay in the deep. (184)

When asked about halibut spawning behavior, 13 out of the 15 harvesters who had heard the meeting presentation prior to being interviewed reported that the findings of the tagging study that halibut spawning occurred in deep water in the winter made sense to them and they did not disagree. Some justified this conclusion by reporting that while they had seen other fish in spawning condition before and thus had knowledge of what a spawning condition fish looked like, they had not seen spawning condition halibut during the halibut fishing season:

> No, I've never ever seen spawn in a halibut. Like, you cut a codfish open in the summer, you see the pink spawn, the eggs, but halibut, never seen, no. So I figured then they must spawn in the winter. (562)

> I have seen it in turbot, odd time, not very often, you see the great big, big sac of roe when you gut turbot, the big female turbot, that’s only two or three times I've seen it. […] I don't think that I have [seen halibut spawning gonads], no, not in summertime. (772)

However, five harvesters did express some surprise at the PSAT analysis conclusion which went against their previous assumption, shared by one of the harvesters interviewed before hearing the presentation, that halibut were spawning during the great abundances harvesters were seeing inshore in the warmer summer months:

> That's why I thought maybe they came in close to mate because there are so many patches. (992)

> We all naturally assumed, always, that they came to the shallow water to spawn in the summertime. That's what we assumed because the warmer temperature. (332)

> I hadn't given a lot of thought about why the fish are coming in shallow in the summer times. I just automatically assumed that it had something to do with spawning […] but having said that, what clicks in now is because you never ever saw those mature roes. (112)

Two harvesters maintained that their belief was neither wrong nor irreconcilable with the findings from the PSATs, suggesting that halibut may not all spawn at the same time, and reporting having seen halibut with spawning condition gonads during their fishing season:

> The only thing that I would go a bit baffled there is that he's saying halibut spawn in winter, and I'm of the opinion opposite of that. I thought the spring. […] Because, all throughout the year when we're halibut-ing, I see the roe and some […] almost looks like it's ready to spawn, and some more it look like a piece of rag, like there's nothing there. […] All through the year, both. […] So, they don't all spawn at the same time or I don't know, but, that's what it seems like to me. (212)

> My belief, the halibut comes in to spawn, […] And I've been seeing halibut showing off to the bottom of this truck here. […] My great, great grandfather, his great, great grandfather, everybody, believe halibut come to shallow water to spawn. […] Summertime mostly. They'll come up when the water is warmer I guess. […] I'm not saying when they come up a little bit in January, February that they don't spawn. […] But our belief they do come in shallow water and spawn. (523)

The three others that reported ever seeing spawning condition gonads in halibut had seen them outside of their direct for halibut fishing operations as part of another fishery or a halibut survey:

> In the spring of the year they're pretty well spawned out. […] Mostly we've seen, the ones that we've seen spawning was up in the [turbot] nets up in the deep water so must go in the deep water to spawn. […] I've seen [halibut with spawning condition gonads] around June. (181)

> In the Fall of the year, oh yes, everyone that we clean. […] Yes, in the Fall of the year they are really, really ready, yes. […] November, December, I think. I don't know when they really do spawn but really they are getting ready at that time. […] Suppose they does it in deep water in the winter time, I don't know. (184)

3.4 Discussion

Atlantic halibut in the Gulf of St. Lawrence is currently at one of its highest levels of abundance in decades, as estimated from commercial landings and DFO multispecies bottom trawl surveys (DFO, 2019a). The fish harvesters interviewed in the present study demonstrated this with their comparison of past and present longline catch rates. The change in CPUE they described, translated from the FHK reports into comparable fisheries science units using the formula described by Neis et al. (1999), reflected a similar increasing trend over the last three decades to that reported in the latest stock assessment of Gulf of St. Lawrence halibut (DFO, 2019a). Gulf halibut also supports one of the highest value groundfish fisheries in Atlantic Canada (Government of Canada, 2020). High value and increased abundance present a good outlook for the future of the fishery, so long as effective management strategies taking into account current information continue to be employed going forward.

Fish harvesters, at stock assessment and public meetings and during FHK interviews, highlighted potential spatial resource conflicts between Atlantic halibut and other industries, including other fisheries. They specifically mentioned trawl fisheries as having a strong impact on historical abundances of halibut, and mentioned the redfish trawl fishery as a possible future concern. A moratorium was placed on redfish trawling in 1995 due to population declines in Gulf of St. Lawrence redfish, and since then redfish has only been targeted by an index fishery from June to October (Senay et al., 2019). The redfish recruitment events of 2011, 2012, and 2013 are the largest recorded by the DFO research survey, and this has been reflected in the redfish survey catches in recent years (DFO, 2020b). As a result, managers are exploring the possibility of reopening the historical bottom trawl redfish fishery (Senay et al., 2019). Adult halibut are poorly sampled in government survey trawls because they are strong enough to outswim the research survey trawls. However, the DFO survey trawls in the Gulf of St. Lawrence only tow nets for 15 minutes at 3 knots (Bourdages et al., 2019). By contrast, commercial fish trawling, such as that for redfish, may tow nets for up to 4 hours at 2-5 knots, long enough that even adult halibut are susceptible to being caught (Neilson et al., 1989). Atlantic halibut up to 165 cm have been reported as bycatch in the Gulf redfish trawl fishery (Senay et al., 2019). Halibut bycatch returned to the water may survive, but the stress of being crowded in the trawl net and handled aboard the vessel may induce mortality. Also, the size range of halibut capable of being caught by redfish trawls, between 15 cm and 165 cm according to Senay et al. (2019), includes sizes well below the size at maturity of halibut (females: 103 cm, males: 80 cm) reported by Sigourney et al. (2006). The juveniles who have not yet had an opportunity to spawn may also have poorer survival, as better halibut trawl bycatch survival has been found to be associated with larger fish, in addition to smaller overall catch weight, shorter trawl tow durations, and shorter on-deck handling times (Neilson et al., 1989; Rose et al., 2019).

In addition to bycatch, trawling for redfish may also affect halibut by disturbing spawning behavior. As the interviewed halibut harvesters pointed out, the redfish fishery is expected to occupy the same grounds as it had in the past, the deep channels in the Gulf of St. Lawrence (Gascon, 2003; Senay et al., 2019) (Figure 3.2). Reports of the redfish fishery also noted that while redfish were landed year round, the highest numbers were during the winter months (January to March) (Senay et al., 2019). The deep channels in the Gulf during the winter are the same locations and times that electronic tagging studies have found Atlantic halibut to be spawning (Le Bris, et al., 2018; James et al., 2020; Gatti, et al., *in press*) (Figure 3.2). Fish behave differently during spawning than during other times of the year, and this can also affect their interaction with fishing gear, as demonstrated by Morgan et al. (1997) who found that Atlantic cod (*Gadus morhua*) were less likely to actively avoid trawls during spawning time. Gear modifications or alternative gear types are a potential solution for mitigating the negative effects of trawling on spawning species. As possibilities for reducing halibut bycatch in a winter redfish fishery, midwater trawls are being explored (Senay et al., 2019), as well as halibut escapement systems operating on behavioral or physiological differences between target and bycatch species (E.H. Carruthers, *personal communication*). However, halibut in the present study were found to perform as many as 13 spawning rises a day (mean 1.93) up to 284 meters (mean 68.95 m) off the seafloor (Appendix G) between January and April. While midwater trawls may avoid the halibut on the seafloor, they may interrupt the halibut employing spawning rises, and halibut may be forced to abort spawning rises in avoidance of midwater trawls. Some halibut studied in captivity as part of artificial rearing experiments have been observed with obviously swollen, i.e. ready to spawn, gonads that then regress without release of eggs (Haug, 1990), suggesting that spawning may be restricted in response to stressors such as poor handling during egg stripping. Should halibut spawning rises be interrupted by midwater trawling, it is unknown whether the halibut will respond by attempting another spawning rise, or by rejecting spawning during the apparently threatening conditions.

The issue of spatial overlap between other high value industries, specifically oil and paper pulp effluent, was also raised by meeting attendees following presentations of PSAT results. An environmental impact assessment for the “Old Harry” oil project, albeit a project now on indefinite hold, was released in 2011, and Corridor Resources Inc. was issued a license to explore the oil and gas prospects at the proposed drilling site (Stantec, 2011). When the environmental impact assessment was conducted, the halibut satellite tagging program in the Gulf had not yet started and the only data incorporated into the assessment was from DFO summer trawl surveys (Stantec, 2011; DFO, 2013). Because halibut are located in shallower and more coastal waters in the summer at the time when surveys are conducted, halibut distribution maps did not extend into the deepest central Gulf channels and halibut were classified as having a "moderate" level of occurrence with the drilling site (Stantec, 2011). In their review of the environmental impact assessment, Fisheries and Oceans Canada indicated that data from the DFO summer surveys did not cover some areas of the Gulf, and other data sources with greater Gulf coverage and from other seasons should be incorporated (DFO, 2013). The environmental assessment was revised in 2013 to include data from January surveys in the Cabot Strait from 1994-97, which showed halibut distribution in the deep channel in the Cabot Strait, in proximity to the drilling site, although the "moderate" level of occurrence classification remained (Stantec, 2013). Since the environmental impact assessment was revised, PSAT research has revealed that the "Old Harry" proposed drilling site is located within one of the main halibut spawning grounds in the Gulf of St. Lawrence (Figure 3.2). Naturally, because this new information on halibut spawning location was not available before, no mention was made of halibut spawning location in the Gulf of St. Lawrence in either environmental impact assessment document, although winter was reported as spawning time (Stantec, 2011, 2013). The oil industry disturbs natural habitats with construction and operations, and oil in the environment from leaks or spills can cause further habitat damage as well as disease and death in fish species (McIntyre, et al., 1982). Neglecting to include in environmental impact assessments going forward the current knowledge of the importance of halibut winter residence in deep channels for spawning could lead to detrimental impacts on the Atlantic halibut population.

Effluent discharge into the southern Gulf from the Nova Scotia paper pulp mill, Northern Pulp, was also identified as a potential impact to halibut migrating into the southern Gulf in summer (Figure 3.2). Environmental impact assessment in relation to their Replacement Effluent Treatment Facility Project did not include halibut in the original project registration document or appendices in January, 2019 (Northern Pulp, 2019a). The Focus Report in October, 2019, mentioned halibut in the appended Marine Environment Impact Assessment which classified the likelihood of Atlantic halibut occurrence in the local assessment area as "low" (EcoMetrix, 2019; Northern Pulp, 2019b). The geolocation of halibut migrations in the present study show halibut occupying shallow inshore waters in the southern Gulf in the summer, the same depth and proximity to shore as the nearby area where Northern Pulp effluent is being discharged (Figure 3.2). While the results of the present study do not show any halibut migrating directly into the Northern Pulp effluent area, James et al. (2020), using a previous version of the geolocation model, did show one Atlantic halibut moving directly into the Northern Pulp effluent location in June. The benefits and drawbacks of using one geolocation model over the other are outside of the scope of the present study. More importantly, both versions registered that the depths occupied by at least one (of 62) halibut during the summer were inshore enough in the southern Gulf to be affected by land-based wastewater discharge. Pollutants in wastewater from paper and pulp industries can expose fish to chemicals that may complicate their reproduction (Hewitt et al., 2008), and can change the species evenness of the planktonic community (Yen et al., 1996) which could affect the food web. Stakeholders who heard the presentations of the PSAT project, which included results from James et al. (2020) available at the time, recognized that halibut should have been considered in the environmental impact assessment, and subsequent public comments in response to the Northern Pulp environmental impact assessment Focus Report included halibut summer migration data from James et al. (2020) (Public Comments, 2019). This demonstrates the importance of collaboration between scientists and stakeholders and communication of research results.

Halibut tagging identified important ecological characteristics of the Gulf population, but it was through discussions with fish harvesters and communication of results to interested parties that the implications of the findings such as potential user conflicts were revealed. This use of FHK to address different but complementary research objectives to those of a traditional scientific study (e.g. electronic tags: biology and ecology; FHK: history and context) is one application of FHK into fisheries research. Another application of FHK is to address the same research objective as a traditional scientific study and compare results (e.g. electronic tags and FHK both used to identify migration patterns). Fish harvesters can corroborate or elaborate on the findings of scientific studies with their own experiential evidence (DeCelles et al., 2017). Analyses of PSATs found that halibut return to one of two general depth ranges following winter migration to deep water, one very shallow inshore (~50m), and the other farther offshore (100-300m) (Gatti et al., *in press*). The interviewed fish harvesters also recognized this differentiation in distribution between the halibut they are catching inshore during the fishing season, and the halibut they know, whether from past fishing experience or from seeing halibut bycatch in the deeper water turbot fishery, are still offshore. Previous studies combining FHK and traditional scientific methods have identified sub-populations and complexities in Atlantic cod populations (Murray et al., 2008; DeCelles et al., 2017). Whether the distinction in halibut distribution found in the present study is representative of two sub-populations, as one harvester suggested, is unknown. What is known is that both PSAT analysis and FHK reported the same notable distinction between halibut distributed in shallow water in summer, and those that remained deep.

However, FHK and more conventional scientific studies do not always come to the same conclusions, as evidenced in the present study by the disagreement between the findings of the PSAT analyses and fish harvesters' opinions on the timing and locations of halibut spawning behavior. One third of the interviewed harvesters believed that the high abundances of halibut they see in the warm shallow water in the summer are indicative of spawning behavior. Interestingly, the same opinion was already noted among Gulf of St. Lawrence fish harvesters over sixty years ago (McCracken, 1958). Their opinions are not unfounded. Other commercial fish species in the region spawn in high-abundance aggregations (e.g. Atlantic cod: Rose, 1993), or warm, shallow waters (e.g. capelin: Crook et al., 2017). Harvesters are also familiar with species having offshore as well as inshore spawning areas (Atlantic cod: Lawson and Rose, 2000; capelin: Crook et al., 2017), which one harvester proposed might be the case with halibut. To date, there have been no direct observations of halibut spawning in the Gulf of St. Lawrence, and while there may be ample scientific evidence to support the interpretation that halibut are spawning in deep channels in the winter (this thesis, Chapter 2), this is not proof that the fish harvesters' different experience is wrong. Nor does one discrepancy invalidate fish harvesters' knowledge. On the contrary, in the same way that the fish harvesters' responses to the findings of scientific studies can reveal perspectives and implications not previously taken into account, discrepancies between FHK reports and traditional science can identify issues that may need further attention or study. For example, a study of FHK interviews of pelagic longline fish harvesters revealed limitations to bycatch assessment methods, relevant to bycatch species conservation efforts (Carruthers and Neis, 2011). Also, FHK interviews of career redfish harvesters revealed misrepresentations in the reported landings of the size distribution of historical redfish catches, an issue that would need to be addressed in the management of any new or existing redfish fishery (Duplisea, 2018). Used in this way, even discrepancies between FHK and other data sources can provide valuable information to resource managers.

3.5 Conclusion

The findings of the present study emphasize the value of communicating with stakeholders, designing study objectives to address the research needs identified by their industries, and incorporating their knowledge into the analyses of results. Co-construction of research agendas with resource users and maintaining positive relationships with stakeholders throughout the research process is of great importance for incorporating research findings into resource management and conservation (Stanley and Rice, 2007; Brooks et al., 2018). Electronic tags can reveal a lot of valuable ecological information about species' movement and behavior, but stakeholder input provides the perspectives on how that ecological data fits into the greater context of the marine resource, shared between multiple industries. Involving fish harvesters in the research intended to improve and maintain the fisheries that support their industry, and responding to the issues they identify as important areas in need of research, also acknowledges their value and that they are the ones directly impacted by any management measures that result from the fisheries research (Mackinson, 2001; Berkström et al., 2019). Thus, when managing any marine resource within which multiple industries may impact each other in space and time, combining knowledge from scientific sources as well as stakeholder perspectives can go a long way to identifying potential conflicts which steps can then be taken to resolve.

3.6 Figures

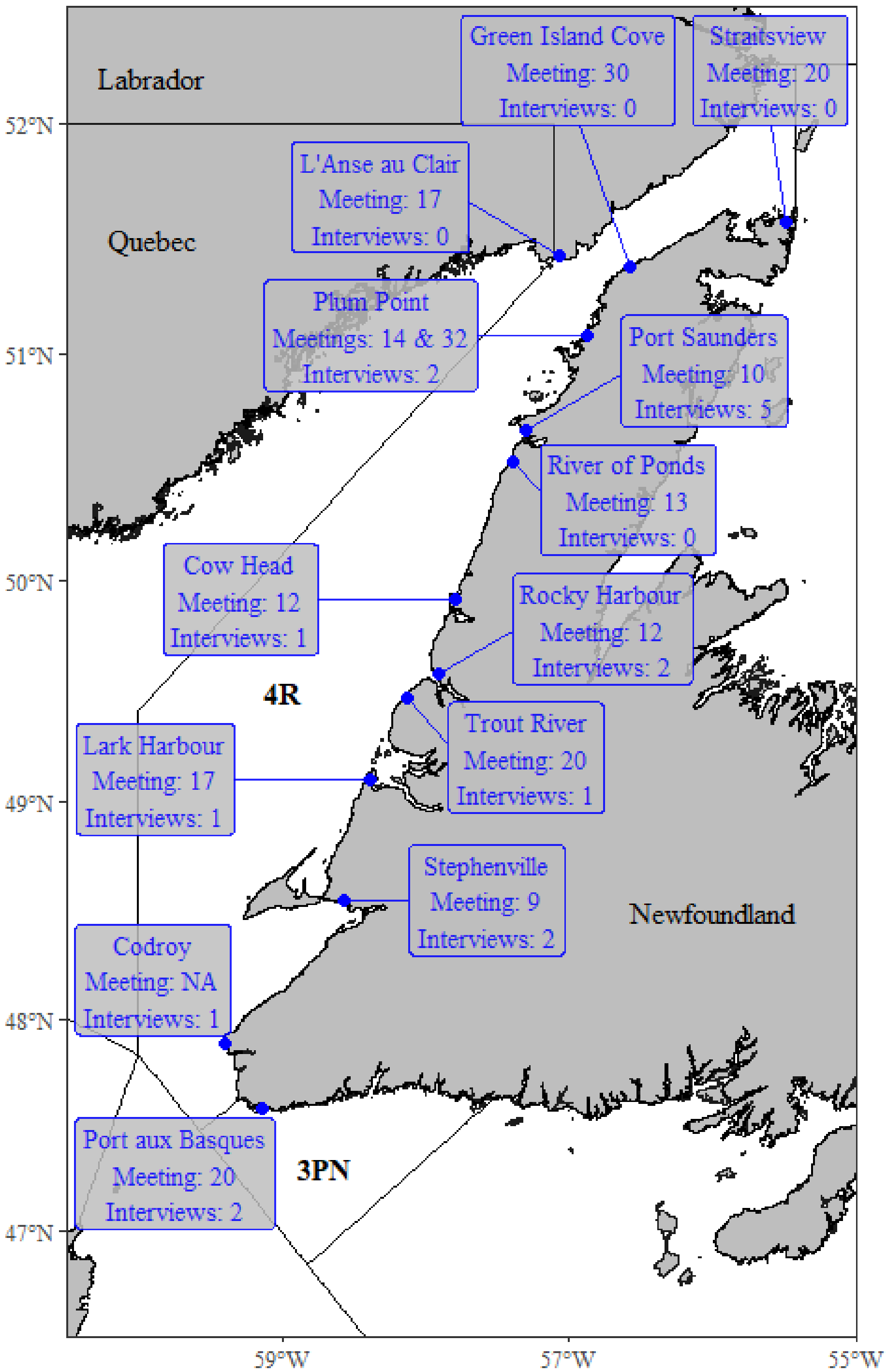

Figure 3.1: Public meeting and interview locations with halibut harvesters from western Newfoundland and Labrador and counts of meeting attendees and interview participants.

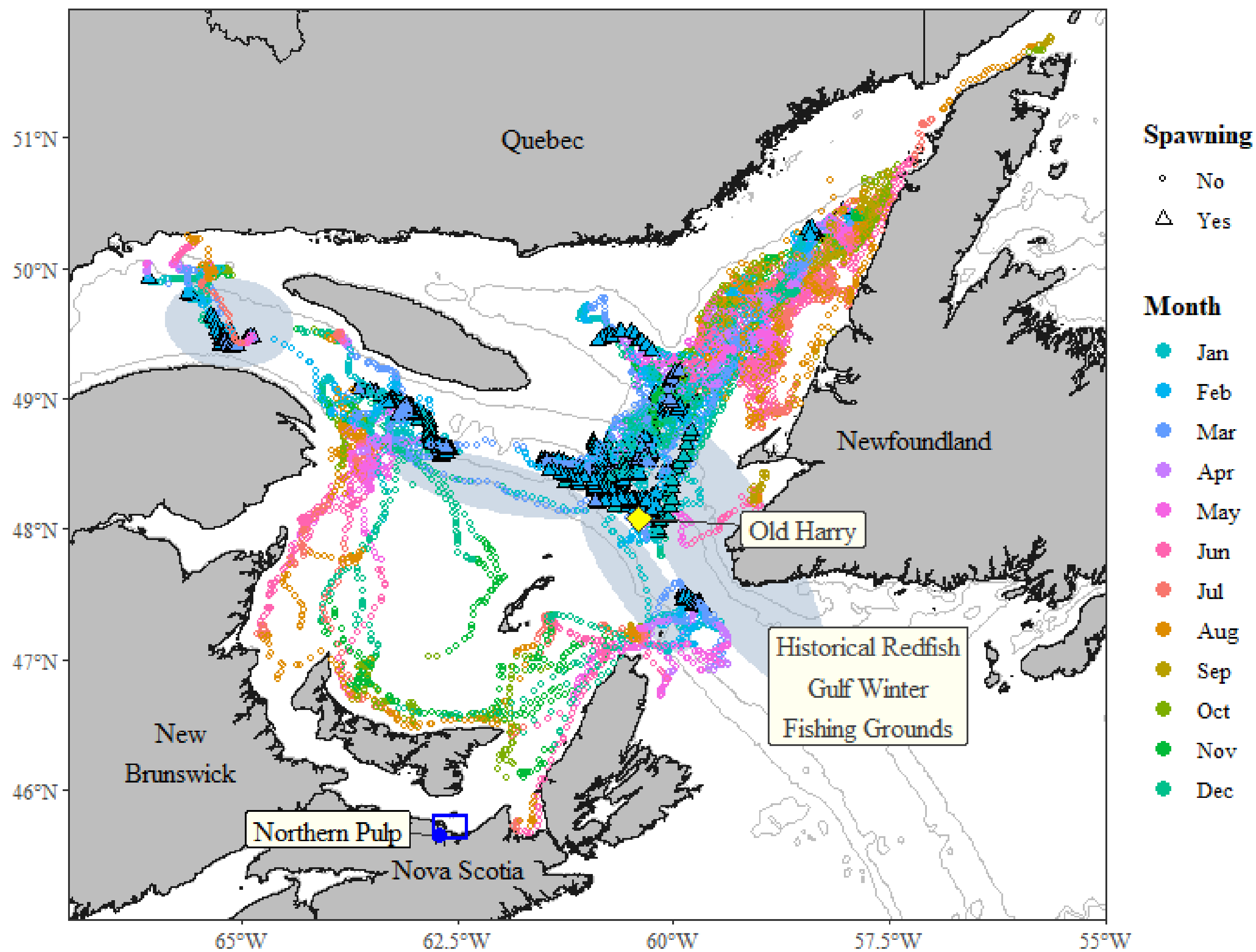

Figure 3.2: Halibut migration tracks, spawning locations, and overlapping industries

Figure 3.2 continued: Migration tracks for 62 Atlantic halibut tagged in the Gulf of St. Lawrence. Spawning periods are highlighted by triangles outlined in black. In relation to halibut distribution are shown the areas of greatest historical winter redfish fishing effort in the Gulf of St. Lawrence (shaded area) (estimated from Gascon, 2003, Figure 4.10: Distribution of redfish effort (hours fished) based on commercial logbook information from 1988-1992), the "Old Harry" drilling site (yellow rhombus) (Stantec, 2011), and the Northern Pulp facility (blue point) and expected area where effluent concentrations will be detectable (blue rectangle) (Northern Pulp, 2019b).

Chapter 4: Conclusion

The high value Atlantic halibut fishery in the Gulf of St. Lawrence is currently managed with limited data and no population dynamics model (DFO, 2019a). Trends in population abundance are based on fishery catch rates, and DFO multispecies bottom trawl surveys which are ineffective at sampling adult halibut (DFO, 2019a). A longline survey and conventional tagging program were developed in 2017 to provide missing information on population abundance, growth, and mortality rates, but these data are not yet incorporated into the stock assessment (DFO, 2019a). Recent findings from PSAT tagging studies about halibut migrations and essential habitats have been included in stock assessments and in the development and improvement of the halibut longline survey (Murphy et al., 2017; DFO, 2018; Le Bris et al., 2018; DFO, 2019a). The present study provides new information on halibut spawning behaviors, factors explaining recent halibut abundance, and potential risk of conflicts with overlapping industries that are valuable contributions to developing effective Atlantic halibut management and conservation plans in the Gulf of St. Lawrence.

The high resolution data available from 36 physically recovered PSATs enabled confident interpretation of the unique extreme rises in the winter depth profiles as spawning behavior. Spatial and temporal overlap of female and male spawning rises met necessary criteria for fertilization of eggs. Also, the female spawning rises typically occurred at 2-4 day intervals, consistent timing with known ovulatory rhythms (Norberg et al., 1991) and egg batch hydration patterns (Finn et al., 2002) of Atlantic halibut, which supports the interpretation that female spawning rises each correspond to the release of a batch of eggs. Confidence in interpretation of spawning behavior allowed for detailed characterizations of spawning rises in the context of spawning strategies. As expected based on analyses by Murphy et al. (2017), the number of spawning rises per individual was much greater for males than for females. Male spawning rises did not follow a timing pattern and occurred more frequently over longer periods, likely because males are not constrained by the same physiological requirements associated with producing eggs (Bateman, 1948; Coleman and Jones, 2011). This suggests that males may spawn with multiple females, either as part of a pair or by employing alternative tactics such as “sneaking in” on a spawning pair or joining a group of males spawning in conjunction with the spawning rise of a single female (Bekkevold et al., 2002; Taborsky, 2008; Habrun and Sancho, 2012). Unexpectedly, the difference in number of spawning rises (i.e. egg batches) per female was not found to be related to fish size. Larger females were expected to have higher fecundity, although higher fecundity may be expressed by characteristics not reflected in the number of spawning rises, such as the number of eggs per batch or egg viability (Hixon et al., 2014).

The high resolution PSAT data made it possible to pinpoint the spawning periods and explore the factors effecting variability in spawning time. Halibut spawning in the Gulf of St. Lawrence occurred between January and mid-April with a peak in mid-February. Warmer water temperatures during the pre-spawning period (December to mid-January), when halibut are expected to undergo pre-spawning gonadal development (Haug and Gulliksen, 1988), were found to correspond to earlier spawning start dates among female halibut. This may explain variability in the documented spawning periods for other regions, including the adjacent southern stock, and may be a contributing factor to genetic distinctions between stocks. Exploring the genetic and migratory connectivity between the Atlantic halibut inside and outside of the Gulf is an important next step for ensuring appropriate definition of management units and categorizing distinguishing behavioral features between stocks.

In the Gulf of St. Lawrence, where the water temperature has undergone documented warming (Galbraith et al., 2012; Galbraith et al., 2019), the connection between start of halibut spawning and water temperature also demonstrates a possible impact of further warming due to climate change. Warming water temperatures have been found to induce earlier behavioral events in other species (Kjesbu, 1994; Jansen and Gislason, 2011; Staudinger et al., 2019). One potential consequence of this is a mismatch between when larvae and their planktonic prey are in the water column (Durant et al., 2007) which could affect larval survival and lead to population decline. Also, genetic mixing between adjacent stocks with temperature-differentiated spawning periods may become more prevalent if regional spawning periods begin to overlap as a result of climate change. Another potential consequence of climate change is the possibility of halibut moving to more favorable environments, as has been predicted for many temperate species faced with increased water temperatures due to climate change (Roessig et al., 2004; Pörtner and Peck, 2010; Hazen et al., 2013). Fish harvesters identified this as a possible explanation for why halibut abundance has increased in the Gulf of St. Lawrence. Continued study of the impacts of climate change on habitat selection and prey availability is needed to help ocean managers plan for future shifts in halibut population characteristics as a result of warming water temperatures.

Halibut spawning rises occurred at depths ≥ 25 meters (up to 284 m) off the seafloor. Notably, analyses of PSAT acceleration revealed bursts in acceleration at or near the peaks of the female spawning rises. This momentary change in activity level may coincide with release of eggs. This has implications for egg dispersal and studies modeling ocean circulation to identify larval drift, settlement, and nursery locations (Pepin and Helbig, 1997; Bradbury and Snelgrove, 2001). Currently, physical oceanographers from the Université du Québec à Rimouski are using the spawning rise characterizations presented in this thesis to model halibut egg and larval dispersal and identify possible nurseries areas, currently unknown in the Gulf.

Before PSAT studies of Atlantic halibut were conducted, knowledge of halibut spawning behavior in the wild was limited to a few sampling studies that identified winter as spawning time (McCracken, 1958; Kohler, 1967), and aquaculture studies that looked at environmental effects on halibut reproductive physiology (e.g. Norberg et al., 2001; Brown et al., 2006). This is unsurprising, because sampling spawning halibut in the deep channels of the Gulf of St. Lawrence is difficult due to sea ice and lack of surveys or commercial fisheries in the area. As a result, halibut spawning behavior has never been directly observed, and even the findings of this PSAT study are interpretations. Some fish harvesters are of the opinion that halibut spawn inshore in summer when the harvesters are seeing halibut in great abundances during the fishing season. To gain more direct evidence of halibut spawning time and location, halibut need to be directly sampled during the expected spawning time, and the maturity stage of their gonads identified preferably by histological analysis. Additionally, plankton tows looking for halibut eggs and larvae could be done in locations and at depths where PSAT analyses revealed halibut spawning rises to occur, or in areas where circulation models predict halibut eggs and larvae to have drifted. To address the fish harvesters' opinion that halibut are also spawning inshore in summer, parallel sampling to that done in winter could be done in summer where and when harvesters identify halibut spawning to be occurring.

The behavioral characteristics of Atlantic halibut revealed through analyses of PSAT data have important implications for future management of the Gulf ecosystem shared among multiple fisheries and other industries. Local halibut harvesters, at industry meetings or during interviews, identified overlaps between the halibut population and Gulf industries that they anticipated could have detrimental impact on halibut abundance and productivity. Geolocation of PSAT data revealed that halibut occupy the deep central channels of the Gulf during the winter, and then migrate back to either middling depth channels or very shallow inshore waters in the summer (Gatti et al., *in press*). The halibut harvesters also recognized this migration behavior from their history fishing halibut, including the differentiation in halibut summer depth preference found from the PSAT analyses, which may indicate sub-populations of halibut or local complexities to the halibut stock previously unconsidered in stock assessment. This summer depth distinction has informed the design of the Gulf halibut longline survey to ensure that stratified-random survey sampling includes both shallow and deep stations. Furthermore, future study of unique behavioral or genetic features that distinguish subsets of the halibut population could improve the fisheries interaction with the species. The very shallow inshore ranges of some halibut also suggest that halibut may be affected by land-based industries discharging wastewater into the coastal environments, such as Northern Pulp in the southern Gulf. Thus, as fish harvesters pointed out, halibut need to be included in environmental impact assessments of land-based industries releasing effluent, and considered in the spatial planning of those industries.

Halibut also need to be recognized in the management of ocean-based industries including other fisheries. Halibut harvesters identified mortality of halibut bycatch in trawl fisheries as a primary cause of low halibut abundances in the past, and they were concerned that future trawl fisheries, such as the proposed redfish fishery, would have the same harmful impact. In order to minimize impact on halibut, redfish fisheries management needs to implement protocols to increase halibut bycatch survival (Rose et al., 2019) and explore other fishing methods such as midwater trawls that reduce contact with halibut (Senay et al., 2019). Halibut harvesters also indicated that the proposed redfish fishery in the Gulf of St. Lawrence is expected to occupy the deep Gulf channels in the winter, the same place and time that the PSAT analyses revealed halibut to be spawning. Halibut spawning rises utilize sometimes hundreds of meters of the water column. Thus, avoidance measures such as midwater trawls may still have an impact by interrupting spawning rises, even if bycatch is low. Additionally, a species' response to anthropogenic stressors can be different during the spawning period than during the rest of the year (Morgan et al., 1997). Fisheries management needs to take into account that impacts may be different during the spawning period than during another season.

This also applies to oil and gas industries, such as the “Old Harry” project, the proposed site of which is located in an important halibut spawning area. Incorporating all available knowledge on potentially impacted species into the environmental impact assessment for a project is crucial for accurately representing and planning for the effects an industry may have on an ecosystem and enabling management to support ecosystem maintenance.

The combination of electronic tags and fish harvesters’ knowledge in this thesis was key to revealing characteristics and vulnerabilities of the Gulf halibut population. PSAT analyses identified migration and spawning behaviors that fish harvesters could put into the context of Gulf-wide spatial management, identifying potential overlaps with other industries. Such collaborative research with stakeholders, addressing research needs they identify and communicating research findings to gain stakeholder perspectives, is a valuable tool for integrating relevant information into ocean management in order to promote and maintain healthy marine ecosystems.

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Appendices

Appendix A: Exploration of spawning rise detection methodology

Spawning rise detection was critical for meeting the objectives of the present study. Because depth profiles varied between tags, finding appropriate criteria to define spawning rises was difficult, and many methods were attempted (Table A1). The first method of detecting spawning rises was the visual method described in the Methods section of Chapter 2 and favored for the duration of the study as the detection technique for male halibut and as a method of confirming the automated detection method employed on the time series for female halibut. The visual method, detecting a spawning rise as any rise ≥ 25 meters off the seafloor based on reports of halibut spawning rise minimum depths by Armsworthy et al. (2014) and Fisher et al. (2017), was admittedly limited. There was more confidence in the detection of female spawning rises because the shape of rises tended to be similar among the other rises per fish, and timing of rises often conformed to regular time intervals. There was much more variation in rise shape among male rises, and no evident timing pattern to assist in rise detection. So while an automated spawning rise detection method could be employed on female time series, the visual method was the most objective method of rise detection for the male rises explored for the present study, and hence was the method relied upon for male rise detection.

Automated detection of spawning rises was first attempted with the R package “anomalize” which is designed to identify anomalies in a time series. Because the spawning rises present as unusual behavior from the rest of the year, reaching anomalous depths for the season, the reasoning was that they could be treated as outliers and thus detected using this package. The biggest challenge with using this program with the depth time series of Atlantic halibut is that the range of “normal” for a halibut is the seafloor depth measurements, which are the maximum depths recorded each day. The anomaly detection program was designed for time series for which the range of “normal” was centered along the time series, outliers therefore not only being points that go anomalously above the normal range, but also below. As a result, adjustments had to be made to the function parameters to widen the range of “normal” enough that it encompassed the seafloor as much as possible. The problem with this was that in widening the range of “normal”, the chances of accidentally including a presumed spawning rise as “normal” increased.

After exploration of the results of different parameter values, those that best served the data sets in the present study were selected. For removal of the data decomposition, that is the season and trend inherently part of the time series, method = “stl” was selected. This method fit a loess curve at the resolution of the trend parameter. The loess curve was better at detecting the seafloor as “normal” than the other data decomposition method which calculated the range of “normal” around the median of the data at the resolution of the trend parameter. The trend parameter for this data was set to 1 day to maximize the probability that the loess curve would fit to the actual measurements of the seafloor. The other data decomposition parameter, frequency of seasonality, was set to 12 hours to account for tidal change (12.5 hours was not an option).

The anomaly detection followed the data decomposition. There were two methods for anomaly detection, one which uses interquartile range (method = “iqr”), and the other which uses a loop of t-tests (method = “gesd”) to identify outliers from “normal”. The “gesd” method was considered more accurate because it is iterative, removing the outliers as it detects them through the time series. However, because this method uses a loop function, it took quite a bit longer than the “iqr” method. For the data in the present study, the difference between the results of both methods was minimal, so the “iqr” method was used, despite the “gesd” preference, to make the best use of time.

The parameters for anomaly detection defined the data points that could be “normal” and those that would be outliers. The parameter “max_anoms” was set to 0.9, allowing 90% of points in the time series to be outliers, not because 90% of the points were expected to be outliers, but so that there was minimized risk of missing any outliers. The alpha level defined the range for each day (the trend parameter) that could be “normal”. The alpha parameter was the most difficult to define because the internal function calculations that defined what alpha actually was were unclear, so the choice was quite subjective. An alpha value of 0.01 was chosen for the present study in an effort to maximize the success of using one alpha value for both females and males. The range of “normal” defined by the 0.01 alpha level revealed a number of outliers to be counted as spawning rises that was fairly comparable to the results of the visual detection method for males, and was inclusive of the results of the visual method for females (Table A1).

The automated detection of spawning rises using the “anomalize” package was rejected because of the subjectivity in defining the alpha level, and because of the inconsistency in detection success from tag to tag. Alpha of 0.01 was chosen as the best of all the options, but it was not without problems. Anomaly detection was affected by the change in seafloor depth from day to day, which for some fish was minimal across the year but for others was quite variable, especially from season to season. The resolution of the tags (2 minutes for 2013 tags, 15 seconds for 2014 and 2015 tags, and 5 seconds for 2017 tags) also affected the number of points that could be counted as outliers. The sex of the fish had the most obvious effect on how many rises were detected at the given alpha level, probably because more frequent rises among males were detected by the program as more "normal" than the more infrequent rises of the females. It was debated whether to use an alpha level of 0.01 for males only and use for females a lower alpha level (0.005) that produced results more similar to the visual method. There was no justification besides fitting to the results of the visual method for using a different alpha level for females and males, especially considering that ecologically, "normal" for halibut, the seafloor, should be the same for females and males. With so much uncertainty in the rise detection by the anomaly detection R package, the method was rejected.

First order depth difference, an indication of ascent/descent speed, was also considered as an automated rise detection method without the use of an anomaly detection R package. The rises during the spawning period, more extreme in rise distance than rises at any other point in the year based on gross visual inspection of the time series, were expected to be undertaken at faster speeds than other rising events. This had been seen to be the case for the one female exhibiting spawning rises from the 2013 tagging year; first order depth differences were much higher for the spawning rises than for rises elsewhere in the time series (Fisher et al., 2017, Supplementary Material). However, this methodology broke down with the higher tag resolutions after 2013. For tags with 15 sec. or 5 sec. resolution, the maximum first order depth difference possible based on the physiology of Atlantic halibut was lower than for tags with 2 min. resolution. While the cumulative change in depth for all the time records from the beginning of a rise to the peak was still greater and in many cases (not all) faster than rises at other times in the year, the first order depth difference was not characteristically greater for spawning rises than other rises throughout the year. As a result, first order depth difference as a spawning rise detection method was rejected.

The speed of the full rise, using time and distance from the start of rise to the rise peak, was not feasible as a rise detection method for the present study because it would have required the manual measurement of every rising event in the entire time series, which was not considered a necessary prioritization of time because the results were not expected to be vastly different than those of the visual spawning rise detection method. Instead, a five-minute centered running mean was taken for the absolute value first order depth difference time series, and a limit was determined to qualify spawning rises, as explained in the Methods section of Chapter 2. Spawning rises were counted as those events at which the change in depth according to the running mean time series exceeded the average running mean change in depth for the entire time series plus twelve times the standard deviation of the running mean change in depth for the entire time series (this arbitrary limit selected after extensive preliminary analysis).

A visual inspection of the true depth time series followed the automated spawning rise detection process to confirm that the events detected as spawning rises by the automated method conformed to the most commonly detected events that were interpreted as spawning rises. These spawning rises were generally over 25 meters in distance from seafloor to peak. Spawning rise shape had a peak depth that was not maintained for more than a few time records at highest resolution before descent to the seafloor was initiated, and generally the ascent and descent speeds were fairly balanced. Therefore, events that qualified as spawning rises according to the speed-based automated detection method, but were shorter than 25 meters in distance or had a shape on the depth profile inconsistent with the standard profile, such as a maintenance of near peak depth for several minutes, or an uncharacteristically slow ascent but an extremely fast descent, were not accepted as spawning rises in the final data set used for analyses in the present study. Also, because Atlantic halibut are known to spawn eggs in batches over a spawning period, isolated rises that did not occur in repetition with other rises were not considered to be associated with spawning a batch of eggs, and were thus excluded.

Additionally, in a few cases, events in the time series became apparent as having consistent distance and shape as the standard spawning rises, but were not detected by the automated detection method because the speed of these events was slower than others. These events were accepted as spawning rises with caution, but understanding that biology is variable and no spawning rise detection method is perfect, especially with the standing caveat that spawning rises for Atlantic halibut have never been directly observed in the wild.

As stated in the Methods section of Chapter 2, this automated detection was successful on female time series, but failed for male time series, so the visual method alone was used to detect male spawning rises. Isolated rises not considered to be associated with a spawning period were excluded.

Table A1: Spawning rises detected using different detection methods. An example tag for both sexes (female and male) and for each tag resolution (2 min, 15 sec, and 5 sec) was used to demonstrate the difference in rise detection. The "anomalize" R package analysis was run with three different alpha levels. Two minimum speeds (5 and 10 meters per tag resolution time) using first order depth difference were used as limits to isolate spawning rises. A minimum change in depth limit on the running mean depth time series (time series mean + 12 times time series standard deviation) returned the best results, but did not work on male time series.

	Females			Males		
Tag Res:	2 min	15 sec	5 sec	2 min	15 sec	5 sec
Visual method	8	5	7	53	138	44
"anomalize" R pkg.						
$\alpha = 0.05$	227	596	1119	447	1027	1672
$\alpha = 0.01$	35	16	111	25	162	105
$\alpha = 0.005$	9	4	13	3	32	23
1st order depth diff.						
≥ 5 m	11	19	5	123	16	11
≥ 10 m	6	4	0	54	7	3
Limit on running mean of depth diff.	8	5	7	NA	NA	NA

Reference

Fisher, J.A.D., Robert, D., Le Bris, A., Loher, T., 2017. Pop-up satellite archival tag (PSAT) temporal data resolution affects interpretations of spawning behaviour of a commercially important teleost. *Animal Biotelemetry* 5. https://doi.org/10.1186/s40317-017-0137-8

Appendix B: Effects on timing and number of spawning rises modeled with R-INLA

Generalized linear models were run using the R package “lme4” as described in the Methods section of Chapter 2. This was a frequentist analysis returning p values as indications of explanatory power of covariates on the variation in the response variable.

For comparison, GLMs were also run using the R package “INLA” (Rue et al., 2017). This is a Bayesian analysis tool, and as such does not present p values. In the absence of p values, “statistical significance” was inappropriate terminology to apply to the GLM results. Instead, the “statistical importance” of a covariate in explaining the variation in the response variable was decided based on the posterior distribution of the covariates. If the distribution did not include zero (i.e. was completely negative or completely positive from 2.5th percentile to 97.5th percentile), the covariate was considered statistically important in explaining the variation in the response variable. If the posterior distribution included zero (i.e. had 2.5th percentile and 97.5th percentile values with opposite signs), the covariate was not considered statistically important because this situation would suggest that the beta value (i.e. the slope of the regression line) for that covariate could credibly be positive, negative, or zero.

The same GLMs run with “lme4”, described in the Methods and Results sections of Chapter 2, were run with “INLA”, testing the effects of several environmental and individual factors on the date of the first female spawning rise and the number of female spawning rises. The first GLM tested the effect of water temperature during the season prior to spawning (Dec. 1 to Jan. 15), fish size, spawning location, spawning year, and tagging location on the start of spawning. The model error was assumed to follow a normal distribution and this assumption was verified during model validation by plotting residuals versus fitted values, and versus each covariate in and not in the model (Zuur and Ieno, 2016). Model selection was implemented using the deviance information criterion (DIC) (Spiegelhalter et al., 2002). The second GLM tested the effect of mean water temperature during the spawning period, the date of the first spawning rise, fish size, spawning location, spawning year, and tagging location on the number of spawning rises per female. The model error was assumed to follow a Poisson error distribution with a log link function, and this assumption and risk of overdispersion were verified during model validation (Zuur and Ieno, 2016). Model selection was implemented using the DIC (Spiegelhalter et al., 2002).

The date of the first spawning rise was best explained by a GLM that included the effect of tagging location and preseason growing degree day (Table A2 and A3). The model predicted a statistically important negative relationship between the start of spawning and the water temperature during the season prior to spawning. The model also predicted a statistically important difference in start of spawning between fish tagged in Quebec and fish tagged in Newfoundland and PEI, predicting that spawning occurs earlier among fish tagged in Quebec than in the other tagging areas. The difference between the start of spawning of fish tagged in Newfoundland and PEI was not statistically important.

The number of spawning rises was found to be independent of fish size and mean temperature during the spawning period. The number of spawning rises was best explained by a GLM that included the effect of tagging location (Table A2 and A3). However, the model did not predict the relationship to be statistically important.

Table A2: Generalized linear model selection using DIC scores. Continuous covariates include fork length (FL), preseason growing degree day (GDD), first spawning rise date (FRD), and spawning period mean temperature (TMP). Categorical covariates include spawning location (SL), spawning year (SY), and tagging location (TL). Values from Bayesian statistical analysis did not differ from values from the frequentist analysis used in this thesis, Chapter 2.

GLM	Response Variable	Error Distribution	Fixed Effects		DIC
1	Date of First Spawning Rise	Gaussian	Full Model	FL+GDD+SL+SY+TL	188.29
			Covariates of Interest	GDD	180.98
			Selected Model	GDD+TL	178.84
2	Number of Spawning Rises	Poisson	Full Model	FL+FRD+TMP+SL+SY+TL	131.47
			Covariates of Interest	FL+TMP	118.58
			Selected Model	TL	116.59

Table A3: Generalized linear model parameter estimates. Values from Bayesian statistical analysis did not differ from values from the frequentist analysis used in this thesis, Chapter 2.

GLM	Response Variable	Covariate	Estimate	SD	2.5%	97.5%
1	Date of First Spawning Rise	Preseason GDD	-5.614	2.266	-10.091	-1.120
		Tagging Location				
		Newfoundland	Baseline (0)	--	--	--
		Prince Edward Island	-6.845	5.743	-18.170	4.557
		Quebec	-9.811	4.114	-17.928	-1.644
2	Number of Spawning Rises	Tagging Location				
		Newfoundland	Baseline (0)	--	--	--
		Prince Edward Island	0.211	0.197	-0.184	0.590
		Quebec	0.231	0.169	-0.104	0.561

References

Rue, H., Riebler, A., Sørbye, S.H., Illian, J.B., Simpson, D.P., Lindgren, F.K., 2017. Bayesian computing with INLA: A review. *Annual Review of Statistics and Its Application* 4, 395–421. https://doi.org/10.1146/annurev-statistics-060116-054045

Spiegelhalter, D.J., Best, N.G., Carlin, B.P., Linde, A.V.D., 2002. Bayesian measures of model complexity and fit. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 64, 583–639. https://doi.org/10.1111/1467-9868.00353

Zuur, A.F., Ieno, E.N., 2016. A protocol for conducting and presenting results of regression-type analyses. *Methods in Ecology and Evolution* 7, 636–645. https://doi.org/10.1111/2041-210X.12577

Appendix C: Water density and spawning rises depths

Water density was explored as possible explanation for the distances traveled off the seafloor and the peak depths reached by the halibut during spawning rises. Estimates of water density were calculated using modeled temperature and salinity profiles of the spawning locations during the spawning periods of 22 females and estimates of water pressure calculated using the following formula:

$$Pa_h = \rho g h + Pa_{atm}$$

Where Pa_h is the pressure in Pascal (1 Pa = 1 kg/m^2) at depth h, ρ is the seawater density at the surface, assumed to be 1025 kg/m^3, g is the acceleration due to gravity equal to 9.81 m/s^2, and Pa_{atm} is the atmospheric pressure at surface, equal to 101325 Pa. Water density at spawning rise depths was then calculated using the "swRho" function from the R package "oce".

The estimated water density at the peak of the spawning rises of the 22 females analyzed ranged from 1027.13 kg/m^3 to 1027.7 kg/m^3 (mean 1027.54 kg/m^3). Density at the start of the rises ranged from 1027.51 kg/m^3 to 1027.74 kg/m^3 (mean 1027.64 kg/m^3). The difference between water density at the start and peak of spawning rises ranged from 0.008 kg/m^3 to 0.535 kg/m^3 (mean 0.105 kg/m^3).

Pycnoclines were calculated for the spawning period at the spawning location of each individual, and spawning rise peak depths were examined in relation to their position on the pycnoclines (Figure A1). Water density increased with depth along the entirety of the pycnocline, so shallower spawning rises correlated with a generally lower water density than deeper spawning rises. No spawning rises reached the point on the pycnoclines where the change in density per change in depth became steep, suggesting that the halibut may not be targeting a specific water density for peak of spawning rises. The water density remains fairly constant for a wide depth range within which are the spawning rise peaks.

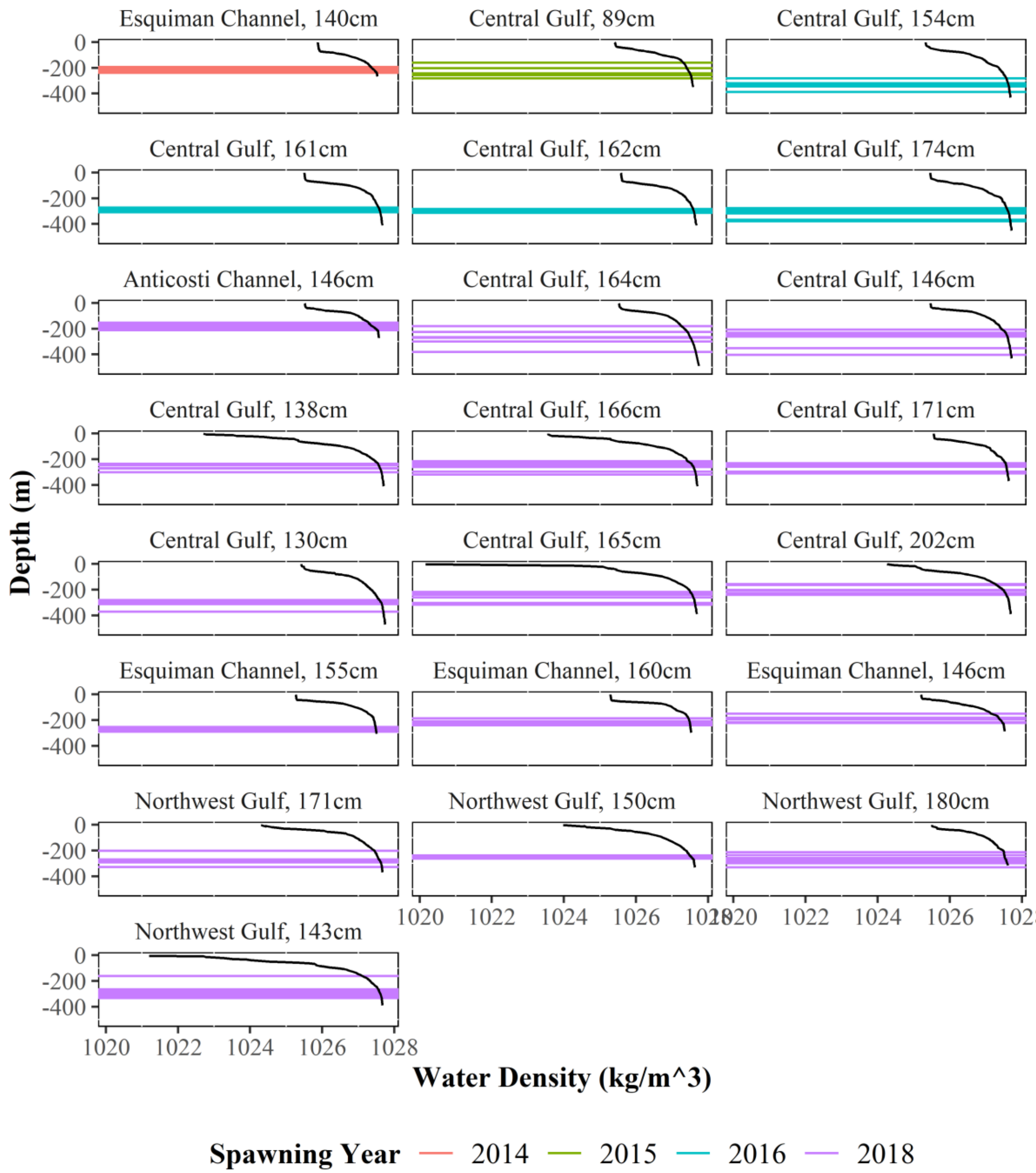

Figure A1: Modeled pycnoclines (black lines) for 22 individuals at the locations and times of spawning for each individual. Horizontal lines represent the peak depths of spawning rises.

Appendix D: Ethics approval letters for interviews with fish harvesters

Interdisciplinary Committee on Ethics in Human Research (ICEHR)

St. John's, NL Canada A1C 5S7
Tel: 709 864-2561 icehr@mun.ca
www.mun.ca/research/ethics/humans/icehr

ICEHR Number:	20192281-MI
Approval Period:	December 19, 2018 – December 31, 2019
Funding Source:	Graduate Research Accelerator Development (GRAD) fund (Administered by MI)
Responsible Faculty:	Dr. Arnault Le Bris Centre for Fisheries Ecosystem Research
Title of Project:	*Use of Fishermen's Ecological Knowledge in understanding Atlantic Halibut behavior in the Gulf of St. Lawrence*

December 19, 2018

Rachel Marshall
Centre for Fisheries Ecosystem Research
School of Fisheries, Marine Institute
Memorial University of Newfoundland

Dear Rachel Marshall:

Thank you for your correspondence of December 18, 2018 addressing the issues raised by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) concerning the above-named research project. ICEHR has re-examined the proposal with the justifications and revisions submitted, and is appreciative of the thoroughness and clarity with which you have responded to the concerns raised by the Committee. In accordance with the *Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2)*, the project has been granted *full ethics clearance* to December 31, 2019. ICEHR approval applies to the ethical acceptability of the research, as per Article 6.3 of the *TCPS2*. Researchers are responsible for adherence to any other relevant University policies and/or funded or non-funded agreements that may be associated with the project.

The *TCPS2* **requires** that you submit an Annual Update to ICEHR before December 31, 2019. If you plan to continue the project, you need to request renewal of your ethics clearance and include a brief summary on the progress of your research. When the project no longer involves contact with human participants, is completed and/or terminated, you are required to provide an annual update with a brief final summary and your file will be closed. If you need to make changes during the project which may raise ethical concerns, you must submit an Amendment Request with a description of these changes for the Committee's consideration prior to implementation. If funding is obtained subsequent to approval, you must submit a Funding and/or Partner Change Request to ICEHR before this clearance can be linked to your award.

All post-approval event forms noted above can be submitted from your Researcher Portal account by clicking the *Applications: Post-Review* link on your Portal homepage. We wish you success with your research.

Yours sincerely,

Kelly Blidook, Ph.D.
Vice-Chair, Interdisciplinary Committee on Ethics in Human Research

KB/lw

cc: Supervisor – Dr. Arnault Le Bris, Centre for Fisheries Ecosystem Research

MEMORIAL UNIVERSITY

Interdisciplinary Committee on
Ethics in Human Research (ICEHR)

St. John's, NL Canada A1C 5S7
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ICEHR Number:	**20192281-MI**
Approval Period:	December 19, 2018 – December 31, 2020
Funding Source:	Graduate Research Accelerator Development (GRAD) fund (Administered by MI)
Responsible Faculty:	Dr. Arnault Le Bris Centre for Fisheries Ecosystem Research
Title of Project:	***Use of Fishermen's Ecological Knowledge in understanding Atlantic Halibut behavior in the Gulf of St. Lawrence***
Amendment #:	***01***

January 28, 2020

Rachel Marshall
Centre for Fisheries Ecosystem Research
School of Fisheries, Marine Institute
Memorial University of Newfoundland

Dear Rachel Marshall:

The Interdisciplinary Committee on Ethics in Human Research (ICEHR) has reviewed the proposed modifications for the above referenced project, as outlined in your amendment request dated December 5, 2019, and is pleased to give approval to the revised consent form and recruitment protocol, as described in your request, provided all other previously approved protocols are followed.

If you need to make any other changes during the conduct of the research that may affect ethical relations with human participants, please submit an amendment request, with a description of these changes, via your Researcher Portal account for the Committee's consideration.

Your ethics clearance for this project expires December 31, 2020, before which time you must submit an annual update to ICEHR. If you plan to continue the project, you need to request renewal of your ethics clearance, and include a brief summary on the progress of your research. When the project no longer requires contact with human participants, is completed and/or terminated, you need to provide an annual update with a brief final summary, and your file will be closed.

Annual updates and amendment requests can be submitted from your Researcher Portal account by clicking the *Applications: Post-Review* link on your Portal homepage.

The Committee would like to thank you for the update on your proposal and we wish you well with your research.

Yours sincerely,

Kelly Blidook, Ph.D.
Vice-Chair, Interdisciplinary Committee on
Ethics in Human Research

KB/bc

cc: Supervisor – Dr. Arnault Le Bris, Centre for Fisheries Ecosystem Research

Appendix E: Interview guide for semi-structured interviews with fish harvesters

Please Note:

- Participation in this interview is voluntary and you may withdraw at any time during the interview if you no longer wish to participate.
- Additionally, you are free to skip any questions that you do not wish to answer.

Demographic

- How long have you been fishing?
- How many years have you been a captain?
- How big is your boat?
- What fishing licenses do you hold?
- Do you specifically fish for halibut or do you catch halibut as bycatch in another fishery?
- How much time do you spend on the water?
    - Months per year, hours per day

Direct for halibut fishery

- How many years have you fished for halibut?
- What fishing gears do you use to catch halibut?
- How do you decide when (what slot of the season) to fish for halibut?
- What time of day do you set your fishing gear?
- How long do you set your gear (soak times)?
- How do you decide the location and depth to fish for halibut?
    - Does it vary with time of year?
- Under what circumstances are you more likely to catch smaller/bigger fish?
    - Does it change over time/location?

Bycatch halibut in another fishery

- What species do you target when you catch halibut as bycatch?
- What time of the year/ of the day are you most likely to catch halibut as bycatch?
- What location and depth are you most likely to catch halibut as bycatch?

Activity

- Migration
    - Can you speak to halibut migration patterns at all?
        - Where do you find them?
        - What time of the year are they there?
        - How long do you think they stay there?

        - Where do they go when they leave?
    - What do you think of these model migration tracks?
        - Does that make sense with what you've seen?
    - What are the halibut doing in the different locations?
- Spawning
    - Where/when do you think the halibut are spawning?
        - What makes you say that? Have you seen evidence to suggest spawning in that location/time?
    - Have you ever seen spawning condition halibut gonads?
- Feeding
    - What kind of bait do you use?
    - Do halibut eat that in the wild?
        - What do they eat?
        - Do they eat the same stuff all year?
        - Do they feed all year?
    - Have you seen halibut stomachs with small halibut in them?
- History
    - Have you noticed any changes in halibut distribution and migration between when you started fishing for them and now?
        - Why do you think that is?
    - What do you think are factors explaining the relatively recent increase in halibut abundance?

Conflicts with other activities

- Based on your knowledge of halibut movement and the fishery, can you think of any conflict with other human activities in the ocean? With other fisheries?
- How do you think we can address conflicts between different fisheries or fishing vs other human activities in the ocean?

Final question

- Would you like a summary of results once I have analyzed them?
    - If so, what is your mailing address?

Appendix F: Additional responses from fish harvesters' knowledge interviews

Time of day to set gear

All the fish harvesters reported early morning, just before or after sunrise, to be the best time of day to set longlines for halibut:

> Just day light. It seems that they're feeding, that's when they're feeding. (183)

> First daylight to the first couple hours after daylight is the best time to set trawl [longline of hooks] for halibut in my opinion. (212)

> Usually in the early hours, late overnight, […] because say around nine o'clock [am], onwards 'til about four or five, they don't seem to bite the bait. (992)

Four said that overnight sets were also successful:

> We find in the morning, […] early in the morning. […] But then sometimes, like now, right now, it doesn't really matter […] I find it's better overnight, you leave your gear overnight, you probably get one on almost every hook. (562)

> Couple hours before daylight. […] I don't know, I guess the fish is feeding, eating better […] Early in the morning. Well, it's not so good in the middle of the day, when the sun gets out and it's hot, […] overnight fishing's usually the best, right? But where there's so many halibut now, it doesn't matter, you know? You haven't got to leave it overnight. (442)

although three others said that overnight sets were unsuccessful:

> Crack of day light. Not before daylight, when you see the light coming in the sky, that's the best time ever. […] Not night time, regardless. Any time after dark, no, because dark is not a good time to set trawl [longline of hooks]. (523)

> Well, some people believe, I'm not sure if it's right, they say, you know, growing, growing daylight, so you know first starting daylight that sometimes that seems to be the best time. Overnight, if you, you know, if you would set late in the evening and overnight, don't seem to be as good, or I haven't found it. […] If you did decide to set overnight, don't seem like they bite as good. Some, and then some more times, you set in the middle, in the midday, and gee whiz, you know, you'll

> get a good haul. But most times, the first set in the morning is the best time, most times. (291)

Two harvesters associated poor times to set gear with encountering bycatch species:

> We try to set for a daylight set, like just an hour before daylight, start setting. And the daylight set we usually find the best. But now the way the halibut is now, how plentiful they are, almost any time of the day is good. But we don't usually set in the dark, because usually you get all other predators. Like skate and all that stuff. But we usually find the morning set the best set. (283)

> Fisherman’s experiences, it's better to set trawl [of hooks] before four o'clock in the afternoon. […] You've got tons and tons of […] hagfish, and they eat the bait off of the trawls [longline of hooks], so it seems like the bait gets eaten off a lot quicker if you set it late in the afternoon […] but other than that, you can halibut fish almost round o'clock, right. (112)

However, six harvesters reported that with the current halibut abundance, they could set anytime in the day and catch halibut:

> Early morning, yeah. […] But you know what, […] that's how it used to be, I think it don't matter, you can go out at any time of the day or night now, set it, set gear and get halibut, like, they’re so plentiful. (662)

> If you wanna talk about old school, like what we find is better, like coming daylight in the morning, or dark in the evening, right? Coming daylight, and rising tide. Now I mean, I’m old school, but with that being said, I mean, […] there’s times you could just set gear at any time of the day or night and you’ll still get fish, right? But there is a preference, and that is like I said, I'm old school, that is my preference. (332)

Halibut distribution patchiness by size

When asked about halibut distribution by size, harvesters commented on the relative abundance of larger and smaller halibut in deeper or shallower water, but these responses were difficult to quantify because “big” and “small” were poorly and inconsistently defined across interviews:

> Usually the shallower water you get bigger fish, and out in the deeper water is an average of, like, smaller fish, but there are some areas along, like, I'd say from a hundred to down to a hundred twenty fathom […], we used to see a bit more smaller fish. (283)

> The shallower the water usually the smaller the halibut. The deeper the water, the bigger the halibut. (662)

> Bigger halibut are in shallow water usually, and it might be […] twenty fathom, fifteen fathom, like that. […] Might be small ones in two or three fathoms outside that […] It's a very fine line between what happens there, yeah that's what I've seen anyway. (772)

and the "nice money fish" (523), i.e. the best for selling, were a middle size range, smaller than some but larger than others:

> You go shallow water, there's more bigger halibut. […] That's what I've seen. […] We used to fish anywhere 10, 12, 15 fathom of water, you get big fish. […] You go deeper, […] you get nice fish, they are thirty, forty pounders, seems that when you come in shallower, you get some of them big ones. (882)

> For the ideal fish, less than fifty [pounds], shallow waters are better, say, we mostly fish less than twenty fathoms, try to. (992)

However, they clarified that this was a "just a rule of thumb" (662), and catches could consist of halibut of a range of sizes at any depth:

> At any given time you could see, you know a brute come up, you know, like a hundred, hundred forty, hundred fifty even over two hundred pounder. […] Anywhere, any given time. […] At any given time, it could be large, small, mixture, it could be anything, right? (332)

> Anywhere from eight fathom to twenty fathom, […] you get all sizes, you get 'em, three hundred, four hundred pounds, all sizes. And you get some small ones, like just under the measure, like, six, seven pounds, not many, cause you're getting them all sizes, thirty, forty, fifty […] right up to four, five hundred pound. (442)

Five Harvesters also reported that they would sometimes see catches with a certain degree of halibut size homogeneity or patchiness by size:

> When you strike on the big one, you strike all the big ones. Or mostly all big ones, you probably get an odd small one. But some place you set and that’s all you'll get is small ones. […] It's just a bunches that you strike, I guess. (353)

> Sometimes you […] start hauling one trawl [longline of hooks] and the majority of the halibut will be small and undersized, then probably in another place you get, it seems the bigger halibut stays together and the smaller halibut kind of, yes. (433)

> Wherever they happen to be, yeah. It seems that they gather together like in schools. Usually, you strike the smaller ones, you strike all small ones. When you get into the big ones, then you’re striking all big ones. You only get the odd small one. (562)

An explanation that one harvester suggested for the size patchiness that they observed was that the halibut are avoiding being preyed upon by other halibut by staying with only those not large enough to be predators to them:

> It seems like the halibut […] group in their own size. So, if you get on the small halibut, […] you can get tons of small halibut. […] and then, once you hit the big fish, you get big fish. So it seems like they're hanging around with […] fish of their own size. […] I guess big fish eat small fish so […], you know, they keep separate. (112)

Bycatch

All the harvesters reported that they have not had a problem with bycatch in the halibut longline fishery:

> No, we're fishing in shallow water, 15-20 fathoms water. Where we fish at, there’s no cod. […] You might get one or two or three fish [cod] or something a day. No bycatch. (442)

> No, not really when we target halibut, no we don't, we don’t get very much cod, we don't get much bycatch when we're targeting halibut. (181)

Eight harvesters mentioned that there may be Atlantic cod bycatch when the cod are migrating through, and two harvesters fishing in NAFO division 3Pn explained that the halibut fishery in 3Pn may close temporarily until the cod have moved on to reduce this bycatch:

> Sometimes, yes. […] We get some of them wolfish, they call 'em, […] sometimes, some of them, but not, mostly it's just halibut. […] Scattered times you will see a few codfish but it's only if they're going through. (772)

> Some codfish in the spring, […] in the spring, of course, the cod are down there, […] In the spring when the cod, of course, in April, the cod are coming back here, right, […] and this is all recognized by DFO science, […] so when you're fishing halibut here in April, the codfish move in. And there comes a point in time where they shut down the halibut fishery for a week, or ten days to allow the codfish to pass through and then you go back at the halibut again, but that's the only bycatch problem. (112)

> Very little [bycatch]. Later in the spring we'll get a bit of cod coming through, they usually shut [the halibut fishery] down for a little bit. […] Usually outside of a hundred fathoms, we get very little cod. (212)

But overall the harvesters did not report a bycatch problem with cod, and reported only infrequently encountering other species:

> That's all depends where you set at; deep water, you don't [get much bycatch]. Scattered turbot in deep water. In the shallow water, you, sometimes, you might get on cod fish, that's all depends, the cod might be there, if you do, you can get a lot of cod fish but that's pretty much it. Yes. Scattered catfish. Wolffish; we call them catfish. (184)

> No problem with bycatch, usually the last so many years, it's just halibut you are catching. You get odd skate or flounders, catfish [wolffish], but not very many. (433)

> Sometimes you might catch a few cod but […] other than that, […] don't have anything. […] You may get a sculpin if you're in the shallow enough water

> sometimes, right, or the catfish, we call it, [wolffish] but no, no problem with bycatch on that, hook and line, that's one good thing with that. (291)

On the other hand, the harvesters reported that Atlantic halibut were frequent bycatch in other fisheries including cod longlining and turbot gillnetting:

> Yes, lots. Right now, our cod fishery here Fall of the year, […] I suppose when the halibut is in-shore, moving back out deep, yes, we got problems with bycatch. (523)

> Yes, we got a big problem with bycatch, especially when we're at the turbot, and when we're at the cod, […] There's a lot of halibut, a lot of halibut. (562)

> I've seen guys fishing in 15-20 fathoms of water, with codfish gear, […] and it comes to the point that we can't get codfish because there is too much halibut on the codfish gear. And at the same day, they could be guys out in 80-85 fathoms of water, and have the same problem. (332)

In NAFO division 4R, the halibut fishing season is a series of one week sessions, and harvesters each sign up for one week during which they will target halibut. The interviewed harvesters that also targeted turbot reported that they would pick the halibut fishing session that was scheduled for after the turbot season ended, in case they caught their halibut quota as bycatch in the turbot fishery:

> Right now we direct for turbot too. We take part of the turbot fishery. And along with the turbot fishery, we got to sign a paper saying that, we're gonna take our halibut as bycatch if we catch any. And usually the quality of halibut you get in a turbot net is not so good as on a hook and line so, and you don't usually bring them in if they're bad, so we put down last slot [i.e. pick the last session in the halibut fishing season] so that we know turbot fishery is finished and then we can go and catch our halibut. (283)

> Me I usually, because I'm turbot fishing, I usually pick the last one, [i.e. the last session in the halibut fishing season] that way if the turbot fishery stays open I can keep turbot fishing. […] I've got to quit turbot fishing when I caught my halibut, so I usually to pick the last of it. (772)

> When you’re fishing turbot, you usually wait ‘til the last one [i.e. the last session in the halibut fishing season] to go and catch something [halibut], because you've got to keep […] your halibut for bycatch when you’re fishing turbot, regardless, right? And if you catch all your halibut when you're fishing turbot, you’re taken out of the water for the two fisheries. (181)

Diet and cannibalism

The harvesters reported baiting their longline hooks with herring (16 reports), mackerel (14 reports), or squid (2 reports):

> Mackerel, herring, squid. […] Over the years I 've found that the softer the baits, seem like better the halibut like it. You know what I mean? Like big chunks with bones and into, it's not so good. (523)

> Mackerel if we can get it, you know, but usually it's herring because it's readily available and got no problem getting the fish with herring. (291)

in addition to “shack bait” (3 reports), which are species that come up on the longline that do not need to be returned to the water but cannot be sold, and so they can be cut up for fresh bait for the next set:

> Herring. That's what we mostly use because it's cheaper bait and we use mackerel sometimes when we get it, and shack from the gear, like if we get different, we might use skate sometimes depending on how dirty the bottom is, […] or we get eels. [Whatever] comes back on the hooks, sometimes we use as baits. (283)

> Our main bait was herring, but we used everything that come on a hook, like shack bait we call it, right? Hard bait. We used everything that come up, cut it up, put it back on the hook for saving on herring. (184)

When asked if the bait species were among the species harvesters had seen in halibut stomachs during gutting, harvesters responded that halibut eat everything:

> They eat everything. Soft shell lobsters, soft shells crab, flounders. (353)

> Yes. Red fish, eels, turbot, cod, I've seen all of it. (283)

> Usually small flat fish, you'd get a sculpin in their stomach…most of the time it's just small flounders and like last year, the sand lance was there, so they were full of lance. (433)

> They'll eat anything, I guess, if they're hungry they'll eat…wolffish or catfish, or conger eels, they'll eat anything […] sculpins, eat them too. (442)

> When we've been gutting them, we've seen 'em with lobsters. rocks, that's the truth, rocks! […] And when we're outside [offshore] you see capelin and stuff in 'em, and shrimp. […] And crab, I know a guy the other year had a five-inch-body crab, […] and it wasn't a real big halibut, he said, either. (772)

> Well, I've seen a lot of things in halibut, we had one, we had a halibut a few years back, it was, it was like two hundred fifty pounds, there was seven lumpfish in it. Seven lumpfish, […] small ones, […] the male lumpfish, not the female. […] And those thorny crabs, you see a lot of those in halibut. I don't see much herring, sometime we might see a herring, but it seems like herring doesn't last in their stomach very long or whatever, dissolves quick. And sculpins, I've seen all of that. (212)

> Everything. I'm seeing crab into them, red fish into them, skate, catfish [wolffish], you name it. […] No I've never ever seen [small halibut in halibut stomachs] in 30 years. That's one thing I can say. (184)

Only one harvester reported ever seeing small halibut in halibut stomachs as evidence of cannibalism:

> I've got halibut in halibut. Oh, yeah, […] So they eat their own. They're a bottom feeder, they'll eat whatever they can find. (562)

although, another harvester qualified that, while flatfish might be evident in halibut stomachs, any further species identification was not possible because prey had been digested:

> Well, sometimes they're gone too far, hard to tell if it was a flounders or if it was a halibut, unless you look like really close, but [they do eat other flatfish], yes, they do. They all eat a fair size flounders. […] And I would say they all eat small halibut too; the bigger halibut would eat the smaller halibut I would think. (433)

Appendix G: Figure A2: Spawning rise characteristics

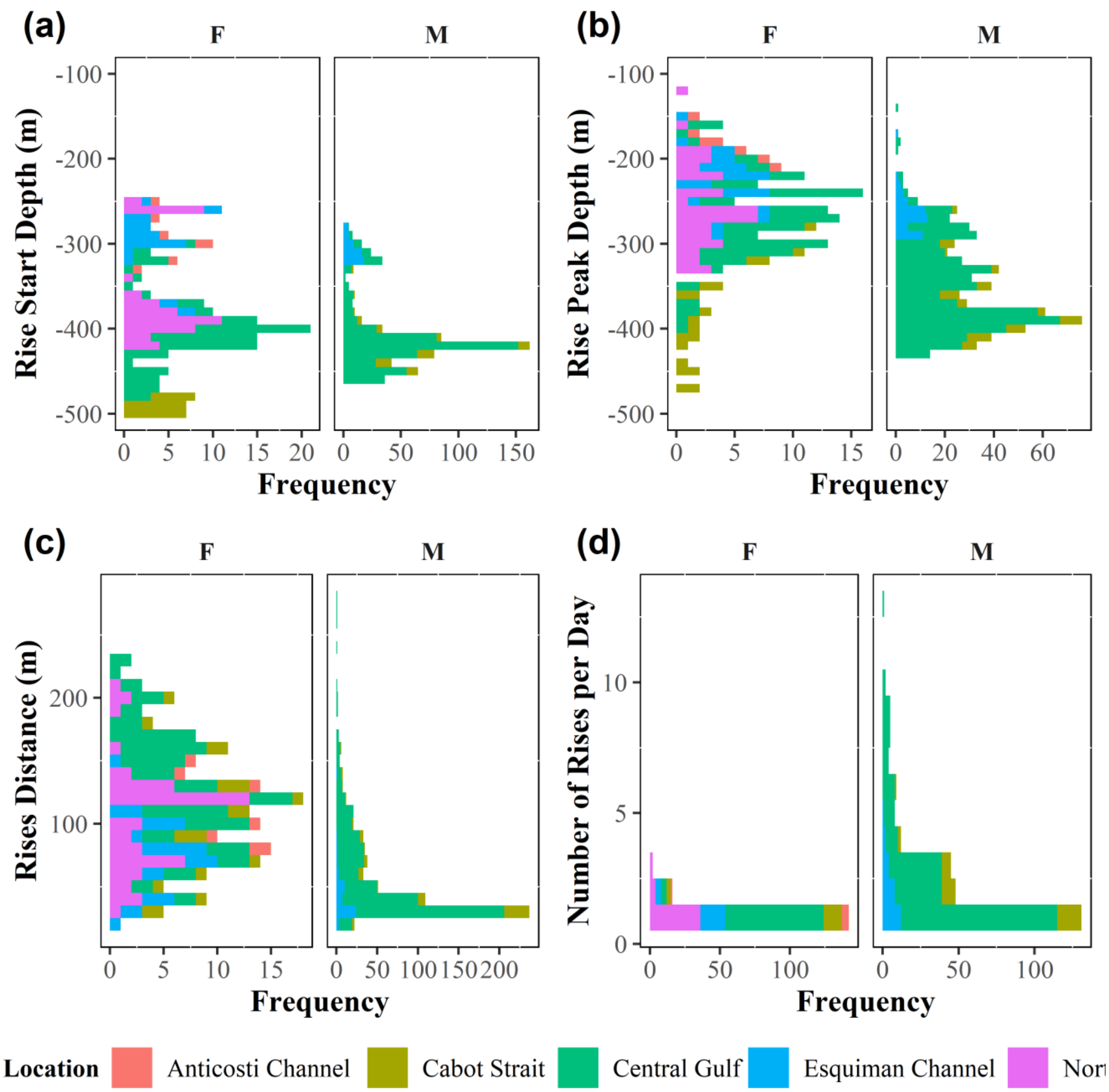

Figure A2: Spawning rise characteristics. A total of 830 rises were analyzed, 180 female rises and 650 male rises.