Bottom Trawl Surveys and MPA's: A Design-Based Inference for Haddock Stock Assessment

by

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Abstract

This thesis provides a design-based inference on haddock abundance based on the DFO's Research Vessel Survey under stratified sampling and investigates the implications/impacts resulting from a MPA area within the survey area. We first provide a brief introduction to survey sampling, in particular stratified sampling which forms the basis of our work. We then provide point estimates through the population mean and, through modifications of the current framework, provide interval estimates and measures of uncertainty though confidence intervals and standard errors. Understanding the affects of an MPA in regards to the probability of inclusion, we then move our discussion towards and alternative method in Domain Estimation to provide updated estimates if we were to assume a MPA was in effect during the survey, which we find had detrimental impacts on data availability. We conclude by providing a discussion on the above findings from our investigation, which demonstrate the limitations if confined to a design-based inference and suggests a movement towards more flexible methods.

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1 Introduction

Since 1970, Fisheries and Oceans Canada (DFO) have been conducting annual ecosystem surveys to monitor the health of various species and monitor trends within the Scotian Shelf region. These surveys are vital in providing information regarding fishery stock, ecological importance, and biodiversity hotspots, assuring proper management of Canada's fishery resources which are valued at approximately 3.2 billion dollars (Benoît et al. 2020, 2). With a wealth of information provided from these surveys, they are often utilized to provide indicators on the population within the survey area. While the goal of these surveys is to ensure the sustainability of a fishery stock and monitor trends within that stock, as a consequence, a major overlap is usually formed with scientific surveys and the implementation of protected areas within the area. Although these protected areas provide a means to ensure sustainable fishery practices, they are often in conflict with the survey in question as it can restrict the survey's ability to collect and provide this information. Despite this, a continual monitoring of the area must be kept, ensuring up-to-date information is being provided and therefore must adapt to these circumstances.

In this thesis, we will examine the trends in abundance for haddock through provision of stratified survey estimates which acts as a population indice for the species and analyse its related error through standard error and interval estimates. Following this, a discussion on the introduction of a protected area will be discussed and how an alternative population indice through domain estimation will be used. The goal of this paper is to provide a design-based inference on haddock abundance through stratified survey estimates and discuss some of struggles that researchers may come across if modifications to the survey area are made in hopes to add to the conversation regarding these protected areas and their associated costs.

2 Overview of Survey Sampling

In statistics, the role of survey sampling is to provide inference on a specific set of elements within a set referred to as a finite population. Although one could in theory provide a complete investigation of the finite population through sampling of the whole population, it is often impractical due to associated costs and can be time consuming depending on the size of the finite population. Survey sampling involves investigation of a partial sample that is chosen within the population with the goal to provide conclusions on the whole population or subpopulations of special interest within the population referred to as domains of interest.

2.1 Probability samples

Consider a finite population of N elements uniquely labeled $1, 2, \ldots, N$

$$U = \{u_1, u_2, \ldots, u_N\}$$

where the size of the population N is known, however, note in practice this is rarely the case. Let y_k denote the variable of interest associated with the element u_k from the population U which is not known beforehand. We are then either interested in providing an estimate for the population total of y or the population mean of y

$$\theta = t = \textstyle\sum_U y_k$$
$$\theta = \overline{y}_U = \tfrac{t}{N} = \tfrac{\sum_U y_k}{N}$$

Rather than all of U, through conducting of the survey, we observe a subset of U, along with the value y_k with this subset called a sample s which is then utilized to construct an estimate for θ. Note s can be any subset of our finite population U, but we often only are interested in samples that are obtained from the probabilistic sampling scheme. Although there are different types of sampling schemes, in general, we denote the probability of observing any specified sample s as $Pr(S = s) = p(s)$, i.e., we assume that there is some function $p()$ that provides the probability of sampling s based on the sampling scheme called the sampling design. For example in the case of a simple random sampling where we observe n of N elements within the population, the probability of observing the given sample is $p(s) = \frac{1}{\binom{N}{n}}$.

In terms of specific elements k within the sample s, given the probability of selecting a sample $p(s)$, the probability that the element k lies within the sample s is given by

$$\pi_k = Pr(k \in S) = Pr(I_k = 1) = \textstyle\sum_{s \ni k} p(s)$$

where I_k is the indicator variable if k is included within a sample called the sample membership indicator of k. Associated with each element of the population is an inclusion probability $\pi_1, \pi_2, \ldots, \pi_N$ called first-order inclusion properties with further orders representing the probability that a given set of elements was included in the sample.

2.2 Estimation From Probability samples

Now that we have an understanding on a sample and the probability of selecting a given sample and its elements, its time to move onto estimation. Previously, we have highlighted that the goal of the survey is to provide an estimate for a function of $y_1, y_2, \ldots, y_N$ called θ. From the sample obtained from U, we provide an estimate for θ in $\hat{\theta} = \hat{\theta}(S)$ denoting that $\hat{\theta}$ was calculated from the elements $k \in s$. With the estimate $\hat{\theta}(s)$ being produced based on a given sample s, it is important to ask given many different samples s from U, how does $\hat{\theta}$ vary given different samples s, i.e., what is the distribution of $\hat{\theta}$. This can be determined by

$$Pr(\hat{\theta} = c) = \sum_{s \in \mathcal{L}_c} p(s)$$

Where $\mathcal{L}_c$ is the set of samples in which $\hat{\theta}(s) = c$

With the goal of providing inference on the whole population, it is important also be able to provide quality estimators. Recall the bias of an estimator $\hat{\theta}$ is given by

$$Bias(\hat{\theta}) = E(\hat{\theta}) - \theta$$

which measures the difference in between the expected value of $\hat{\theta}$ and the true value θ. In the case of $\hat{\theta}$, its expected value is given by

$$E(\hat{\theta}) = \sum_{s \in \mathcal{L}} p(s)\hat{\theta}(s)$$

Ideally, these estimators for θ are unbiased, i.e,

$$Bias(\hat{\theta}) = 0 \rightarrow E(\hat{\theta}) = \theta$$

to provide an accurate representation of the true parameter of interest θ. Therefore the goal of a survey is not only to provide an estimate for θ pertaining to the population, but ideally to provide an estimate that is ideally unbiased or minimally biased.

3 Data

3.1 Survey Overview

The data forming the basis of our analysis today is courtesy of the DFO , providing information corresponding to the Summer Research Vessel surveys. The Summer Research Vessel surveys, preformed in the Scotian Shelf and Bay of Fundy has been conducted since 1970, providing sampling information relating to various fish and invertebrates under a stratified random sampling design collected through bottom trawling.

With the focus today specifically on haddock abundance, the scope of the survey data to be analysed is reduced to only include data pertinent to haddock catch weights. The Stratification scheme is highlighted below, spanning 470 to 495 excluding 479 and 486-489 with strata selected on the basis of representing different depths and habitats (DFO 2020, 3).

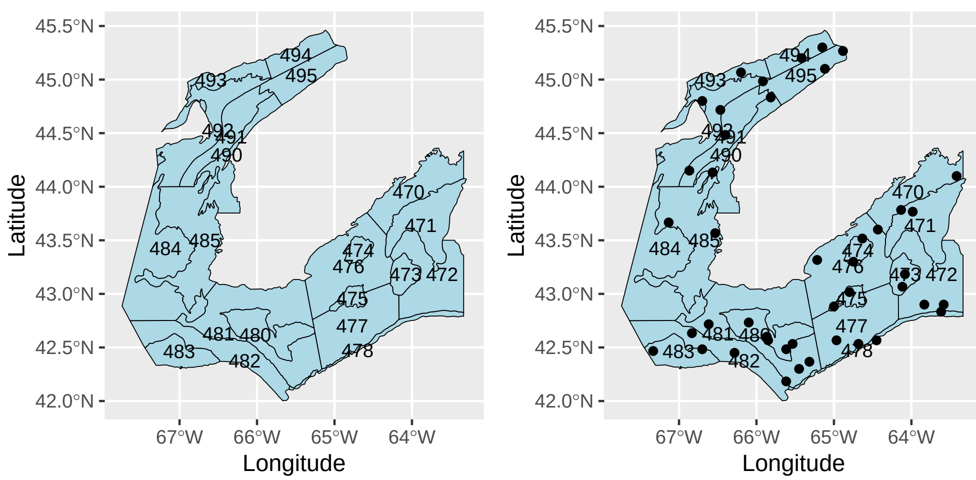

Figure 1: Stratification scheme pertinent to the haddock tow data with the left figure absent of tow hauls and the right figure with tow hauls from the year 1970

In regards to the specifics of the sampling procedure, sampling had occured at randomly selected stations within all strata for each year using a towable unit area of approximately 0.04 square kilometers (sqkm). After the tow was preformed, information such as the strata where the sample was obtained, its biomass in kg, and longitude and latitude coordinates associated with a unique mission ID were recorded.

3.2 Coordinate Reference Systems and Strata Information

With the focus of our thesis relating to spatial data, one overlooked feature can be the proper provision and setting of a coordinate reference system (CRS). The goal of a CRS in essence is to scale a 3 dimensional object such as the earth and project it onto a 2 dimensional space forming a map. With many different types of CRS which may project an object slightly differently compared to others, it is important to be able to distinguish how a quantity is calculated such as location or area as across different data they may be utilizing a different CRS. Once a CRS is identified, proper transformations can be applied to translate coordinates from one reference system to another, allowing the data to be properly aligned to preform proper calculation much like how one would transform all quantities into the same units. This is particularly important to us as we are required to calculate the area of the survey area and what locations are the tows are preformed within the area. This leads to calculations of the total number of possible tows preformed and the weights associated with each strata from their areas:

$N_h = \frac{Area_h}{Area_{tow}}$; Total number of possible tows within stratum h

$N = \sum_{h=1}^{L} N_h$; Total number of possible tows within the survey area

$W_h = N_h/N$; Proportion of the survey area in stratum h

Table 1: General Strata Information in regards to the area, the total number of possible hauls, and the associated weight

Strata	Area (sqkm)	No. Hauls	Weight	Strata	Area (sqkm)	No. Hauls	Weight
470	3023.15	74641.68	0.05	482	3515.87	86807.1	0.06
471	3297.66	81419.51	0.05	483	1639.27	40473.72	0.03
472	4279.91	105671.36	0.07	484	5963.81	147246.83	0.1
473	910.19	22472.54	0.01	485	5404.68	133441.77	0.09
474	559.98	13825.98	0.01	490	2135.29	52720.5	0.04
475	532.8	13154.85	0.01	491	2333.62	57617.33	0.04
476	5101.3	125951.34	0.08	492	3489.11	86146.35	0.06
477	4196.09	103601.83	0.07	493	1465.57	36184.92	0.02
478	707.19	17460.48	0.01	494	1398.66	34533.1	0.02
480	2253.39	55636.28	0.04	495	2019.87	49870.81	0.03
481	6504.97	160608.2	0.11				

3.3 Analysis of Tows

Moving on to the tow data, today we will be providing estimates for haddock abundance based on data pertaining to the Summer Research Vessel survey from 1970 to 2020. Over the course of the 51 years, 3401 tows were recorded with the following number of tows recorded each year:

Table 2: Yearly number of tows recorded in the survey

Year	Tows	Year	Tows	Year	Tows	Year	Tows
1970	46	1983	53	1996	68	2009	77
1971	44	1984	51	1997	70	2010	75
1972	52	1985	53	1998	70	2011	87
1973	50	1986	53	1999	68	2012	81

1974	52	1987	70	2000	69	2013	81
1975	52	1988	71	2001	70	2014	74
1976	53	1989	69	2002	77	2015	82
1977	53	1990	71	2003	84	2016	87
1978	50	1991	70	2004	63	2017	89
1979	54	1992	70	2005	70	2018	73
1980	49	1993	70	2006	80	2019	89
1981	51	1994	70	2007	68	2020	73
1982	55	1995	69	2008	75		

From a plot of the tows preformed in the year 1970 on the survey area, we can see cases where it is apparent that some of these tows were preformed outside of the defined survey area. This may be the case due to many different reasons like an improper identification of what strata the tow originated from, leading us to conclude that it is best in this case to remove these tows from our data set.

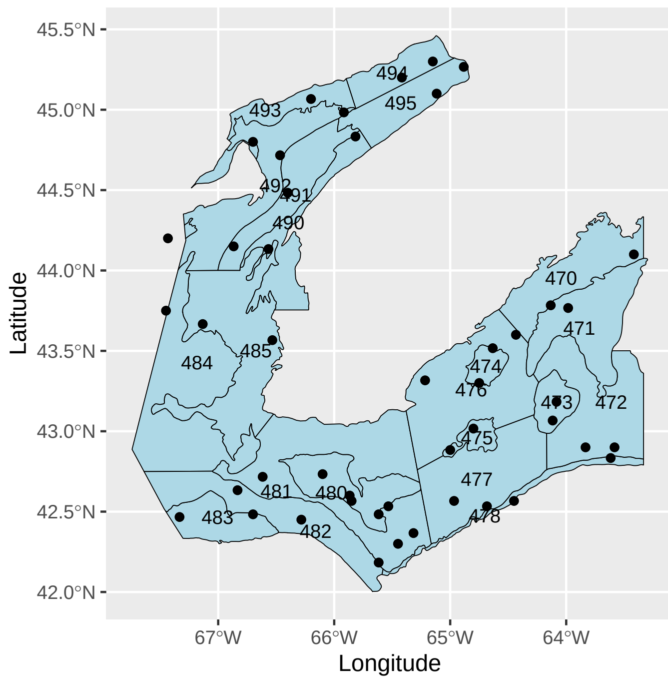

Figure 2: Plot of the survey area with the tows recorded in 1970 without filtering out the tows that are outside the survey area

With the removal of the tows that seemingly fall outside of the survey area, we are left with 3382 tows with the following number of tows recorded in each year:

Table 3: Yearly number of tows recorded in the survey with tows preformed outside of the survey area filtered out

Year	Tows	Year	Tows	Year	Tows	Year	Tows
1970	44	1983	51	1996	68	2009	77
1971	43	1984	49	1997	70	2010	75
1972	50	1985	53	1998	70	2011	87
1973	50	1986	52	1999	68	2012	81
1974	49	1987	69	2000	69	2013	81
1975	51	1988	71	2001	70	2014	74
1976	53	1989	69	2002	77	2015	82
1977	52	1990	71	2003	84	2016	87
1978	50	1991	70	2004	63	2017	89
1979	53	1992	70	2005	70	2018	73
1980	48	1993	70	2006	80	2019	89
1981	50	1994	70	2007	68	2020	73
1982	55	1995	69	2008	75		

Synthesizing the information above, we can also provide the mean number of tows preformed within a year based on data over the course of the 51 years, finding a mean number of tows of just over 66.

Table 4: Mean number of total hauls based on data spanning 1970 to 2020

Mean Yearly Hauls
66.31

We can further provide information on the number of tows preformed in each strata, which we will synthesize the data to provide on measure of this in the mean number of tows preformed within each strata as opposed to providing the number of tows in each strata for all 51 years.

Table 5: Mean number of hauls taken from each strata based on data spanning 1970 to 2020

Strata	Average Hauls	Strata	Average Hauls
470	2.18	482	2.75
471	2.16	483	2.02
472	3.37	484	3.53
473	2.04	485	3.84
474	1.96	490	3.37
475	2.02	491	3.27
476	3.47	492	3.29
477	3.94	493	3.02
478	2.31	494	2.51
480	5.96	495	2.47
481	6.82		

We can see from the above table that sampling within each strata is not equal, as some strata are sampled more than others, with some of the means being even less than two like in the case of stratum 474. This provides some information to us in regards to how low a sample size could be in a given strata, and with some means lower than 2, we'll move on to investigate to see how many strata were sampled from only 1 time within a given year, which will be very important to us later.

Table 6: Year and Strata number where the number of tows preformed in that area was only one

Year	Strata	Year	Strata
1970	470	1978	495
1970	493	1979	476
1971	482	1979	483
1971	484	1986	470
1974	483	1987	495
1976	483	1996	471

Interestingly enough, although we have found 12 separate cases where the number of tows preformed in the strata in a given year is 1, stratum 474 was not identified as one of them. The only reason that this could be the case is if no tows were preformed in this strata in one of the yearly surveys. Providing a table summarizing the frequency of the tows preformed in each year within stratum 474, we can identify that the year 1984 is missing, highlighting that no information in that strata was recorded in that year which is important to identify.

Table 7: Number of tows preformed in stratum 474 in each year which we find no information for the year 1984

Year	Tows	Year	Tows	Year	Tows	Year	Tows
1970	2	1983	2	1997	2	2010	2
1971	2	1985	2	1998	2	2011	2
1972	2	1986	2	1999	2	2012	2
1973	2	1987	2	2000	2	2013	2
1974	2	1988	2	2001	2	2014	2
1975	2	1989	2	2002	2	2015	2
1976	2	1990	2	2003	2	2016	2
1977	2	1991	2	2004	2	2017	2
1978	2	1992	2	2005	2	2018	2
1979	2	1993	2	2006	2	2019	2
1980	2	1994	2	2007	2	2020	2
1981	2	1995	2	2008	2		
1982	2	1996	2	2009	2		

With our analysis of our data complete, we will now move on to discussing the means in providing an accurate measurement representative of the abbundance of haddock within our survey area.

4 Stratified Sampling

In this section, we will focus on stratified sampling, a method of survey sampling in which the population is divided into distinct subgroups from which a sample is selected from each of the strata. Let the population $U = \{1, ..., k, ..., L\}$ denote the overall population, the strata in this case would be the subsection of U represented as $U_1, U_2, ..., U_h, ..., U_L$ where $U_i = \{k : k \text{ belongs to stratum } h\}$ (Sarndal et al. 1992, 61). The utilization of stratified sampling is very popular, especially in our case when the survey organizer (DFO) may have pre-divided the total survey area into distinct geographic groups.

As for why one may choose to prefer a stratified sampling design over simpler methods such as a simple random sample comes down to potential efficiency gains. If we believe that the overall population can be considered rather a combination of various subpopulations with varying effects on the process we are interested in, adding an additional factor in the stratification scheme can lead to more precise estimates with higher efficiency. This has been shown in Smith's paper with the comparison of a stratified sampling design over a simple random sample in regard to efficiency and precision, coming to the conclusion that over a simple random sample, stratified sampling saw decreases in the variance associated with the stratified mean to be 47.2% smaller over utilizing a simple random sampling design (1996, 30).

4.1 Population Estimates Under Stratified Sampling

With the goal of this thesis to provide an analysis of haddock stock and track changes in the haddock stock, we will look towards an estimate that can encapsulate these goals in mind through calculation of the stratified mean, which provides an estimate for the population mean $\theta = \overline{y}_U$. Before we can discuss the formulation of the stratified mean and its relating standard error, we must first introduce some notation:

n_h; Number of hauls taken in stratum h

$n = \sum_{h=1}^{L} n_h$; total number of hauls sampled

y_{hi}; Tow weight of fish caught in set i in stratum h

$\overline{y}_{hi} = \frac{\sum_{i=1}^{n_h} y_{hi}}{n_h}$; Estimated mean abundance in stratum h

$s_h^2 = \frac{\sum_{i=1}^{L} (y_{hi} - \overline{y}_h)^2}{n_h - 1}$; sample variance in stratum h

The stratified mean can be considered an extension of the taking the sample mean as an estimate in regards to a simple random sample from a single population by accounting for the proportion of population that each subpopulation makes up and taking a weighted mean in regard to each of the strata means:

$$\overline{y}_{st} = \sum_{h=1}^{L} W_h \overline{y}_h$$

From the above formulation of the stratified mean, we can see that each stratum contributes $W_h\overline{y}_h$ to the stratified mean $\overline{y}_{st}$. Although we have achieved our goal in determining an estimate that will best suit our goals, it is also important to provide a measure of variability within the estimate which we will provide through the variance or standard error of $\overline{y}_{st}$:

$$Var(\overline{y}_{st}) = \sum_{h=1}^{L} \frac{N_h}{N^2}(N_h - n_h)\frac{s_h^2}{n_h}$$
$$SE(\overline{y}_{st}) = \sqrt{Var(\overline{y}_{st})}$$

Smith (1996) discusses some important underlying features of the estimate $Var(\overline{y}_{st})$, noting in particular that the estimate for the variance is assessing the effectiveness of estimating the mean catch for all N_h possible hauls as the sample mean and he more samples that are observed, the smaller $(N_h - n_h)$ becomes, therefore increasing the effectiveness of estimating the sample mean at the hauls that could potentially occur but were not observed (28).

In terms of our observations, we note that the formulation of the sample variance of stratum h $s_h^2 = \frac{\sum_{i=1}^{L}(y_{hi} - \overline{y}_h)^2}{n_h - 1}$ causes some issues on our part, with often times the number of observations n_h being 1, we find a lack of an ability to properly calculate the sample variance observed in these strata which hinders our ability to provide an estimate for the variance and in turn may complicate further analysis. As for what is to be done to resolve this issue is not so clear. Sarndal et al. briefly discusses this case, noting this to be considered an "extreme" case, and suggests what he calls a collapsed strata technique where pairs of strata are formed (1992, 109). As for the procedure we will take, we will somewhat take advantage of the spatial nature of our data, assuming that adjacent strata are somewhat similar to each other through Tobler's Law of Geography, calculating the sample variance in stratum h in these problem cases to let the given stratum h and all adjacent strata hauls be considered as one single sample coming from stratum h.

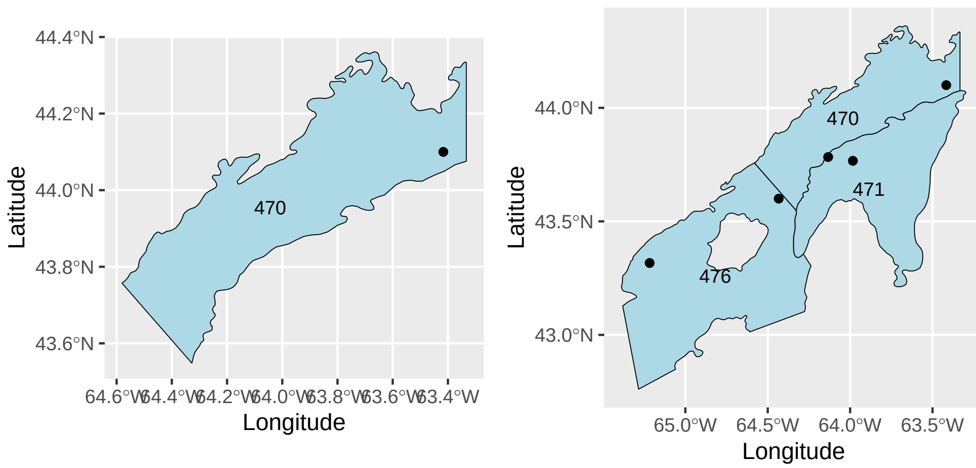

Figure 3: Example of how the sample size for the stratum 470 is artifically increased by accounting for all tow observations in adjacent strata as a unified sample taken from stratum 470, allowing us to preform a proper calculation for the stratum sample variance

Will all of the issues seemingly resolved, we will now proceed to provide the estimates for the stratified mean and relating standard error over all years and provide a time series of the estimates to get a better overall picture of haddock abundance and its fluctuations over time.

Table 8: Table of estimates for the associated stratified mean and standard error of haddock abundance from 1970 to 2020 with the estimate for the standard error relying on the modified strata variance calculation

Year	Mean	SE	Year	Mean	SE
1970	26.06	8.66	1996	54.95	16.49
1971	34.02	9.59	1997	29.75	4.44
1972	16.15	2.12	1998	28.56	5.61
1973	20.86	4.86	1999	37.63	4.63
1974	44.51	11.5	2000	39.62	7.02
1975	25.51	6.57	2001	55.61	10.73
1976	25.98	3.22	2002	43.55	4.99
1977	148	97.94	2003	43.93	18.56
1978	32.66	7.88	2004	26.25	5.75
1979	52.22	18.58	2005	28.38	3.88
1980	65.26	15.77	2006	30.74	4.15
1981	53.07	10.38	2007	35.36	7.61

1982	59.89	15.79	2008	28.66	6.15
1983	31.14	5.88	2009	40.18	9.05
1984	44.89	12.13	2010	29.69	6.39
1985	50.03	14.49	2011	31.56	10.98
1986	37.12	7.98	2012	19.07	3.34
1987	19.52	3.14	2013	24.14	4.38
1988	18.57	2.95	2014	28.04	4.62
1989	14.4	2.34	2015	45.81	6.26
1990	27.34	4.64	2016	40.15	4.99
1991	40.46	10.92	2017	24.94	2.57
1992	23.21	6.56	2018	28.99	4.78
1993	8.49	1.7	2019	18.13	2.02
1994	15.87	3.13	2020	21.64	3.13
1995	32.87	4.41			

Table 9: Example of quantities used to calculate the stratified mean and standard error for the year 2020

Strata	$\overline{y}_h$	s_h^2	n_h	Area	N_h	W_h
470	9.15	3.47	2	3023.15	74641.68	0.05
471	2.14	4.50	3	3297.66	81419.51	0.05
472	12.15	117.14	4	4279.91	105671.36	0.07
473	45.40	246.29	2	910.19	22472.54	0.01
474	30.11	124.78	2	559.98	13825.98	0.01
475	41.84	2.16	2	532.80	13154.85	0.01
476	13.80	198.14	5	5101.30	125951.34	0.08
477	19.45	148.29	4	4196.09	103601.83	0.07
478	6.34	1.20	2	707.19	17460.48	0.01
480	74.47	8381.97	5	2253.39	55636.28	0.04
481	35.18	1364.60	6	6504.97	160608.20	0.11
482	5.58	34.01	3	3515.87	86807.10	0.06
483	10.71	98.77	2	1639.27	40473.72	0.03
484	10.39	12.90	7	5963.81	147246.83	0.10
485	19.75	663.26	5	5404.68	133441.77	0.09
490	51.47	1946.04	3	2135.29	52720.50	0.04
491	70.64	120.37	3	2333.62	57617.33	0.04
492	4.05	10.15	4	3489.11	86146.35	0.06
493	0.87	2.20	3	1465.57	36184.92	0.02
494	5.62	76.70	3	1398.66	34533.10	0.02
495	44.66	5937.50	3	2019.87	49870.81	0.03

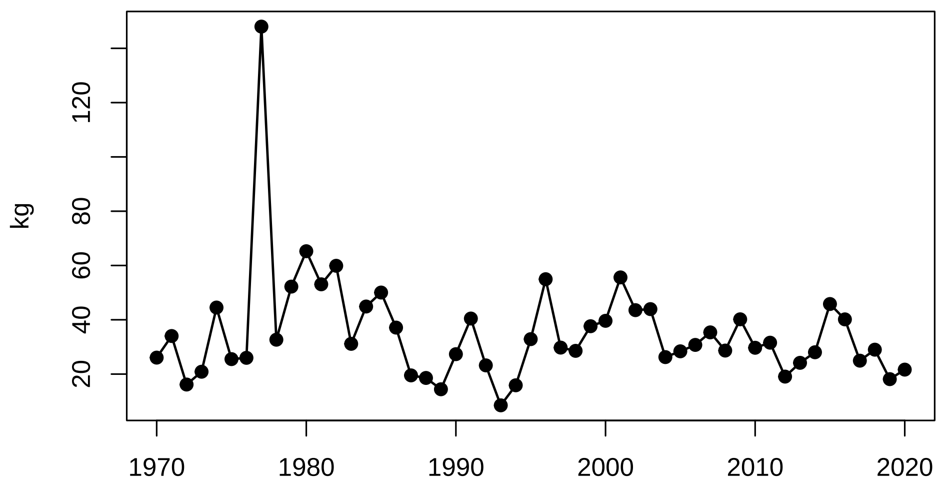

Figure 4: Time series of the stratified mean catch weight of haddock from the Summer Research Vessel survey

As for the exact meaning of the stratified mean catch weight, it implies that over the whole survey area, the estimated mean catch weight per tow is the stratified mean. For example, in 2020 the mean catch weight per tow of haddock was 21.64 kg. From this, we can also produce an estimate for the total weight of haddock within the population since we know the number of total possible tows that could be conducted is $N = \sum_{h=1}^{L} N_h = 1499486$ and thus take this number and multiply it by the stratified mean to obtain an estimate for the whole population. For the year 2020 for example, we estimate a the total weight of the population of haddock within the survey area to be $N \times \overline{y}_{st} = 32448887$ kg.

As for overall trends that can be observed in the time series, we do not observe any general declines or increases in the haddock population but rather a fluctuation mainly between 20 and 60kg, however we note a sharp sudden increase in estimated mean catch weight in 1977 of over 130kg but is not maintained in the following years. We also note the low estimated mean catch weight in the mid 1990's which dips well below all other mean tow weights which upon analysis of our table of estimates occurs in 1993 with a mean catch weight of 8.49 kg.

4.2 Influential Points And Their Effect On The Stratified Mean

With the above time series of the stratified mean, one interesting feature that can be observed is the drastic increase in the mean in comparison to the other years and requires a more careful investigation on our part as to why this may be the case. Upon analysis of the tows retrieved from the year 1977, we can see that there is a major outlier tow of over 2300kg in strata 476 that was taken.

Table 10: Tow data pertaining to the year 1977

Strata	Tow	Strata	Tow	Strata	Tow	Strata	Tow
471	0.00	491	7.41	477	18.90	490	70.00
478	0.00	481	9.00	477	19.76	481	87.94
484	0.00	493	9.33	481	20.12	485	95.67
484	0.00	490	10.50	485	21.00	491	99.40
492	0.00	474	11.55	483	24.50	492	110.25
471	1.75	478	11.81	494	28.00	480	168.00
494	2.33	492	12.16	495	33.35	480	224.70
493	3.50	481	12.25	482	35.00	480	237.56
484	3.71	472	13.50	483	38.64	473	302.65
482	4.38	493	15.00	474	51.88	473	326.81
478	6.46	476	17.18	495	54.25	470	501.20
475	6.56	485	18.26	491	57.75	480	613.50
470	7.00	472	18.67	475	59.89	476	2327.06

With this observation in mind, an important question to ask is how much of an influence does this value have on our estimate? We note that from the equation to calculate the stratified mean, we can conclude that each observation contributes towards the stratified mean by a factor of $\frac{(W_h y_{hi})}{n_h}$. From this, it follows that the proportion of the stratified mean made up by any single observation in the sample is $\frac{(W_h y_{hi})}{n_h \overline{y}_{st}}$. Combining these results together, we now have the means to calculate the proportion of the stratified mean that each observation accounts for and provide a scatter plot to better visualize these results.

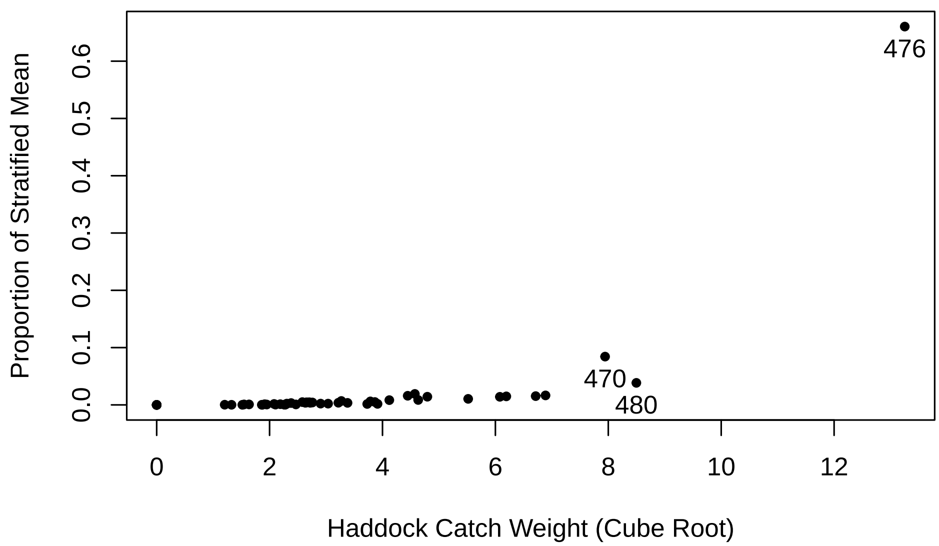

Figure 5: Scatterplot of the proportion of stratified mean agaisnt the cube root of each catch weight for the year 1977

From our above analysis, we find that our outlier observation that we had took note of earlier accounted for over 60% of the stratified mean, concluding that this value has a high influence on the stratified mean as we should observe an equal influence observed across tows had that not been the case. Smith (1996) had come to a similar conclusion in his analysis of haddock abundance in relation to the 1988 eastern Scotian Shelf survey and discusses that the estimate can be made less variable by removing or replacing the observation by the next highest, however does impact the bias in an unknown way (31).

4.3 Interval Estimates

With the provision of estimates for the stratified population mean and its related standard error, the next conceivable step would be to provide an interval estimate for the stratified mean. This allows us expand our analysis from a simple point estimate for the abundance of haddock towards a range of plausible values for our estimate where we believe the true value to lie associated with some degree of confidence. In the sections below, we will discuss various methods in constructing various interval estimates through confidence intervals, highlighting the persistent issues relating to a low sample size in some strata.

4.3.1 t-confidence Intervals

When interested in constructing confidence intervals for an estimate relating to a mean relating to a simple random sample with unknown population variance, it is often times provided through a t-confidence interval. Since we are dealing with a stratified sampling design opposed to a simple random sample, things get a little more difficult in regard to calculating the proper degrees of freedom along with the underlying assumption that the data is normally distributed. Sampling theory suggests that under repeated sampling, $\overline{y}_{st}$ is assumed to follow a normal distribution and its associated degrees of freedom called effective degrees of freedom is calculated by:

$$df_e = \frac{(\sum_{h=1}^{L} g_h s_h^2)^2}{\sum_{h=1}^{L} \frac{g_h^2 s_h^4}{n_h - 1}} \text{ where } g_h = \frac{N_h(N_h - n_h)}{n_h}$$

The above assumption and formulation of the degrees of freedom allows us to calculate a t-confidence interval composed as the following:

$$100(1-\alpha)\% \text{ CI} = \overline{y}_{st} \pm t_{1-\alpha/2, df_e} SE(\overline{y}_{st})$$

One important thing to note regarding the formula to construct the effective degrees of freedom is the denominator of $n_h - 1$. We have previously highlighted that one issue within the DFO research vessel survey is the abundance of only 1 tow within a stratum over the course of the survey. Much like the issues observed in attempting to calculate strata sample variance s_h^2, this results in a value of 0 in the denominator which leads to an inability to calculate the df_e associated with the stratified population mean for those given years. Another issue is the normality assumption, which when analyzing a histogram of the weight of the tows for the year 1977 and the previously presented influence plot, we can clearly see issues with this assumption.

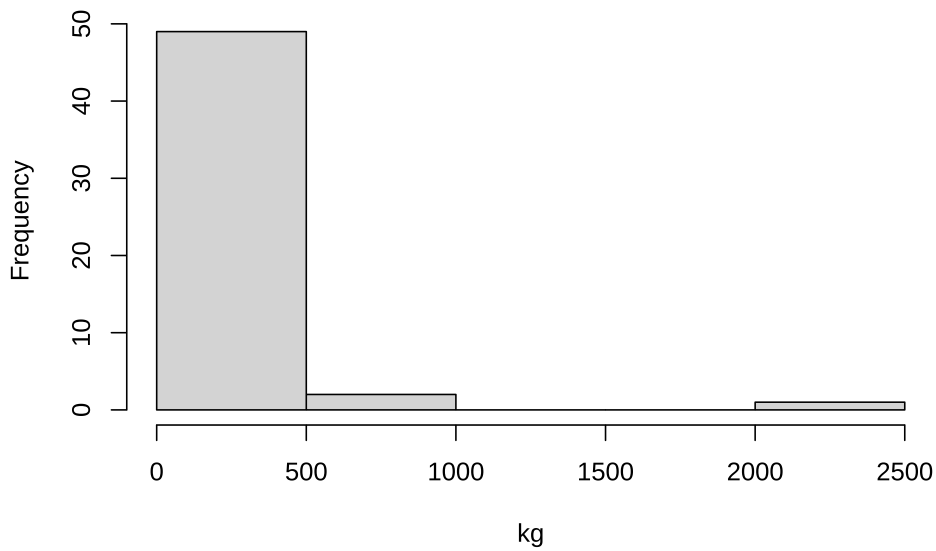

Figure 6: Histogram for the catch weight based on the data from 1977, highlighting that the distribution of the sample tows do not resemble a normal distribution

Although we are limited in provided t-confidence intervals for only years where the number of samples observed in each stratum n_h are greater than 1 and the distributional assumptions do not seem to hold, we provide a 95% confidence interval for the year 1977 highlighted below to introduce the idea. Note that the provided confidence interval is very wide, most likely due to the extreme observation observed highlighted in the influence plot and presents a negative lower bound, which while is of no issue to statisticians, is sometimes hard to explain to the general public when it is well known that the abundance of haddock cannot be less than 0.

Table 11: 95% confidence interval based on the t-distribution for the year 1977 in regards to the mean population catch weight.

2.5%	97.5%
-991.85	1287.85

4.3.2 Bootstrap Confidence Intervals

From the previous section, we found that although a parametric confidence interval can be constructed for the stratified mean, it relies on the assumption that the tows are normally distributed, from which we found does not seem to be the case and is noted that it is rarely met in practice. Furthermore, in our case, we often fail to meet the criteria in the formulation of the effective degrees of freedom as it imposes that the number of hauls be greater than 1 in any given strata, as we have demonstrated that we often observed a strata with only 1 haul which will result in an undefined degree of freedom and affected how we calculated a variance estimate for the stratum. Although we presented a sample of a t-confidence interval using the year 1977, due to the large standard error for the given year due to the large proportion of the mean value coming from an extremely large tow, we found large bounds for the interval extending towards negative values, which intuitively may confuse some people understandably due to the range of values a tow weight can be.

The above section highlights that the limited suggestions for parametric confidence intervals concerning the stratified mean is very limiting, especially in our case, and thus we must turn to non-parametric methods.

One of the most common methods of non-parametric estimation is bootstrapping, a method of resampling introduced in 1979 as a method of computing the standard error of some parameter θ from a random sample from some unknown probability distribution F.

Suppose we have a random sample $\mathbf{x} = \langle x_1, x_2, \ldots, x_n \rangle$ from a population with an unknown probability distribution F. For non-parametric cases, for which we are interested, the empirical distribution, denoted $\hat{F}$, is a discrete distribution which puts probability $1/n$ on each value of the sample, i.e

$$\hat{F}[\mathbf{x} \in A] = \frac{1}{n} \sum_{i=1}^{n} I(x_i \in A)$$

A bootstrap sample is defined as a random sample of size n drawn from the empirical distribution $\hat{F}$, denoted $\mathbf{x}^* = \langle x_1^*, x_2^*, \ldots, x_n^* \rangle$ which is obtained through draws with replacement from the original sample and can be considered to be a randomized, resampled form of $\mathbf{x}$. From this resampling, an estimate for θ can be produced, resulting in $\hat{\theta^*} = s(\mathbf{x}^*)$, some function of interest such as the sample mean, or in our case, the stratified mean. This process is repeated N times, often large as it leads to more precise standard errors and in turn confidence intervals. From our sample of size N of θ^*, we can in turn obtain standard errors from the standard deviation of the N replicates and in turn can construct confidence intervals. This is useful to us as the large presence of obtaining sample sizes of 1 have complicated our ability to calculate proper stratum variances and in turn variances for the stratified mean, therefore impacting our ability to provide parametric confidence intervals.

In our case, due to the design of the survey, we are not concerned with a single overall population but rather numerous subpopulations pertaining to each individual strata. For complex survey designs such as a stratified survey design, instead of resampling from a singular sample from the overall population, we resample the samples obtained from each individual strata. The intuitive extension of bootstrapping in regards to stratified sampling would be what is referred to as the Naïve method, which resamples each strata an identical number of times to the original sample, call it n_h. This Naïve method, although the simplest, has been shown to result in biased estimates of the standard error of the stratified mean which is not ideal. Various modifications to these methods have been suggested to remedy this issue, however the one that we will opt to use is what is known as the bootstrap with replacement (BWR), which adds the condition to randomly resample from a strata's sample either n_h or $n_h - 1$ times (Smith 1996, 33).

To provide an alternative to parametric confidence intervals, we provide bootstrap estimates for the stratified mean and corresponding standard errors along with 95% confidence intervals through 1000 BWR replicates, with the added modification of if the original sample size $n_h = 1$ to always sample n_h times as opposed to $n_h - 1$ times, noting that this results in the bootstrap sample and original sample to be identical if $n_h = 1$. Although this may affect the bias of the estimate in some unknown way, it allows us to accommodate the data and provide an estimate. The modified procedure provided today can be seen as a combination of the Naïve and BWR methods, where BWR is utilized if $n_h > 1$ and Naïve used if $n_h = 1$. The table below highlights our findings, noting that this method opposed to utilizing t-confidence intervals will always produce a result and does not run into any negative lower bounds.

Table 12: Mean, median, and standard error estimates of the stratified population mean produced for haddock abbundance (kg) using bootstrap methods spanning 1970 to 2020 with interval estimates produced using percentiles

Year	Mean	Median	SE	2.5%	97.5%	Year	Mean	Median	SE	2.5%	97.5%
1970	25.89	26.2	6.87	13.67	38.93	1996	55.04	54.22	15.24	27.47	86.64
1971	33.51	33.51	8.29	18.89	49.39	1997	29.94	29.82	4.21	21.39	38.62
1972	16.17	16.14	1.95	12.41	19.89	1998	28.59	28.16	5.19	19.68	39.59
1973	20.79	20.71	4.43	12.7	29.74	1999	37.41	37.48	4.45	28.89	46.35
1974	44.36	44.38	10.04	25.18	63.91	2000	39.49	39.34	6.39	27.9	52.31
1975	25.2	24.94	5.7	14.53	36.86	2001	55.32	53.94	10.4	37.87	78.73
1976	25.18	25.15	2.85	19.77	30.45	2002	43.46	43.27	4.6	34.26	52.13
1977	149.24	150.4	85.96	34.23	262.5	2003	43.07	42.9	17.66	19.08	80.11
1978	31.57	31.42	6.96	18.64	45.25	2004	26.27	26.19	5.41	17.71	37.66
1979	51.97	51.48	9.42	34.9	71.98	2005	28.46	28.22	3.55	22.02	35.79
1980	64.67	64.88	13.91	39.58	91.22	2006	30.67	30.52	3.93	23.29	38.75
1981	53.17	52.83	9.38	32.74	67.58	2007	35.34	35.14	6.9	23.68	47.83
1982	60.02	58.86	14.37	35.85	90.34	2008	28.77	28.33	5.9	18.26	41.06
1983	31.37	31.1	5.36	22	42.5	2009	39.84	39.54	8.32	24.89	57.64
1984	45.45	45.21	11.13	25.65	69.17	2010	29.57	29.39	6.16	18.12	42.86
1985	50.06	50.13	12.71	28.75	70.98	2011	32.14	31.91	10.69	16.33	55.4
1986	36.97	36.71	7.27	24.23	51.78	2012	19.05	18.95	3.13	13.65	25.99
1987	19.63	19.61	2.66	15.01	25.14	2013	24.17	23.93	4.21	15.97	32.87

1988	18.57	18.49	2.68	13.68	24.25	2014	28.25	28.08	4.32	20.19	36.62
1989	14.28	14.22	2.21	10.2	18.87	2015	45.99	45.64	5.7	35.39	58.24
1990	27.49	27.67	4.12	19.46	34.86	2016	40.09	39.91	4.74	31.47	49.87
1991	41.11	40.77	10.25	23.75	63.35	2017	24.87	24.79	2.51	20.17	29.93
1992	22.8	22.38	6.4	12.05	36.58	2018	28.79	28.72	4.4	20.43	37.83
1993	8.45	8.39	1.61	5.53	11.93	2019	18.02	18.07	1.78	14.56	21.55
1994	16.1	15.92	2.81	10.6	22.12	2020	21.58	21.51	2.9	16.45	27.73
1995	32.81	32.54	4.1	25.15	41.11						

5 MPA's and Domain Estimation

With our analysis of the trends in haddock abundance complete, we now shift our focus to how researchers can adapt to potential or proposed changes in the survey area which may have an impact on the information available. Although the area of interest (AOI) had not been implemented during the duration of the survey, it is important to provide a pseudo analysis on its impact through providing an alternative analysis of haddock abundance with the added restriction of the AOI as it can provide insight and stimulate discussions regarding the proposal in place and how it may impact consequent research. While the common belief in the inclusion of a marine protected area (MPA) within the Summer Research Vessel survey may be to simply re-apply a stratified estimate to the modified data to provide inference on the fisheries stock, we will soon find out that this is not the case and will discuss alternative measures.

5.1 What is an MPA?

Canada has adopted the definition of the Internation Union for Conservation of Nature's (IUCN) definition of a MPA as a "clearly defined geographical space, recognized, dedicated and managed, though legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (DFO 2010, 3). Opposed to its naming scheme, an MPA may not be a fully marine area, and can be also a marine component of an otherwise terrestrial protected area. Common reasons cited for the requirement of an MPA include over-fishing, degradation of habitats, and climate change, with the goal of an MPA to help mitigate these impacts. MPA's also vary in the type of restrictions they impose upon the area, as some completely prohibit human activities with year-round protection while others may be in place seasonally to protect species at risk during times of nesting or areas that face greater damages during specific times of the year (DFO 2010, 3). Although the establishment of MPA's is an effective way to protect relating marine life and ecosystems with Canada's commitment to introduce more and more protected areas, it must also consider the associated costs in relation to scientific surveys conducted.

Anderson et al. highlights some of these concerns in his paper with the assessment of a proposed MPA within the western region of Canada overlapping several fisheries surveys and aimed to determine the impacts associated with shrinkage of the survey area on providing accurate population indices through changes accuracy and trend bias compared to the original area. The resulting analysis concluded that although most species population indices faced small impacts in relation to providing an accurate estimate and therefore scientific advice, species who had a large proportion of their density within the area or distribution altered as a result had detrimental effects, therefore reducing the reliability of the population indices (Anderson et al. 4-7). These impacts have been shown to lead to reductions in the ability to adequately detect declines in stock abundance, and thus impact estimates pertaining to stock assessments.

As for why these assessments of abundance are so useful to researchers is reliance on these scientific surveys to provide advice and inform policy decisions in relation to sustainable fisheries management (Benoît et al. 2020, 19-20). The surveys are often carefully designed to provide consistent sampling often through stratified sampling, allowing unbiased population indices well representative of the survey area to be provided and additionally ensuring high precision within these estimates. If the introduction of an MPA chose to restrict or eliminate the ability to preform stock surveillance, we risk the ability to accurately provide these inferences, thus reducing the ability to provide scientific advice. Although other measures such as fishery-dependant data could be utilized to provide similar knowledge, these indices are often not reflective of the actual abundance and risks of failing to accurately detect decreases in abundance as often commercial fishery catch rates have historically provided a positively skewed bias on abundance (Benoît et al. 2020, 20).

5.2 The Fundian Channel – Browns Bank

Now that we have a clearer understanding of the existence and importance of MPA's, we'll now shift our focus to the proposed AOI and potential MPA that has been put forward by the DFO which partially intersects the survey area associated with the Summer Research Vessel survey. The Fundian Channel – Browns Bank is an offshore AOI of approximately 7,200sqkm comprised of two distinct components, the western centered within the Georges Basin and the eastern spanning the Browns Bank, Fundian Channel, Northeast Channel, and continental slope (DFO 2020, 7).

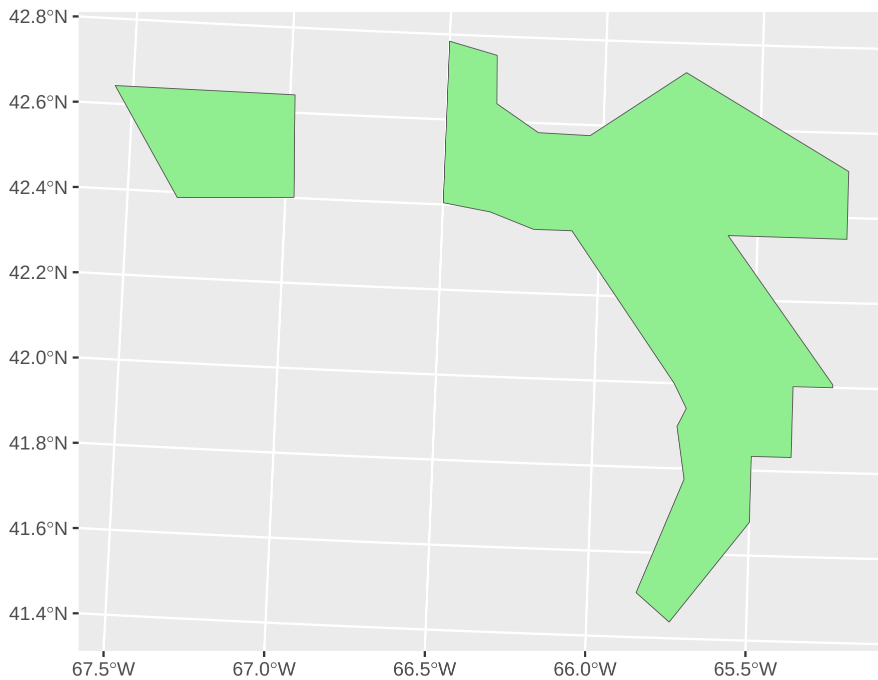

Figure 7: Fundian Channel - Browns Bank proposed AOI highlighted in green within the Scotian Shelf bioregion

Much like other AOI's, the Fundian Channel – Browns Bank is the starting point in the establishment of MPA in the defined area with the goal of conservation and protection of its marine environment. One main concern for the area is the presence of a wide variety of differing habitats such as banks, basins, or channels which provide shelter and breeding grounds for many species of fish and invertebrate species, some of which being species of concern such as the White Hake which is currently under threat (DFO 2020, 7). Other concerns regarding the AOI is its western region and its intersection with the Georges Basin which contains a major migratory corridor to and from the Gulf of Maine. It is important to note that this AOI also overlaps with other pre-defined AOI such as the Northeast Channel Coral Conservation Area (NECCCA) which was put in place with the goal to protect the significant clusters of gorgonian corals which provide many species a habitat such as redfish and juvenile Cod and is known to be very slow growing and low recruiting (DFO 2020, 7, 23).

With the Fundian Channel – Browns Bank area home to many different forms of marine life, of which the DFO has documented the existence of 71 species of fish within the area from their Summer Research Vessel surveys, it is important to understand how this area is pertinent to our thesis in discussing the abundance of haddock within the area. The DFO reports that of the 71 fish species documented between 1970 and 2017, haddock was recorded as one of the top 20 species observed during this time frame, noting that the top 20 ranking species in terms of abundance account for approximately 80% of all fish observed (2020, 12). In terms of specifics regarding haddock, the existence of a major stock was determined in NAFO Divisions 4X5Y, a region which intersects the AOI and is a major breeding ground for the species spanning April to May (DFO 2020, 14). We can conclude from the above information that with the large presence of haddock within the AOI, we expect that some of the tows preformed over the course of the survey may very well have encountered this area and thus will continue with the expectations that a reduction in tows will follow if we choose to isolate tows originating from this region.

5.3 Subpopulations and The Estimation of Domains

With a better understanding of an MPA and its implications on impacts relating to data availability, we'll now move into a discussion on how to accurately provide a measure of haddock stock if we opt to decide that fishing activities were not able to be conducted in the AOI region after the sampling and field work had been done.

Given a survey over the whole population, while providing an estimate for the overall population, researchers may additionally be interested in providing estimates for groups within the population, called subpopulations or domains (Sarndal et al. 1992, 386). This may occur for example if a survey was conducted on a national level and researchers would also like to provide inference on a provincial level, or a survey that includes both men and women and would like to provide insight particular to one gender. In our case, ignoring for now the stratification scheme, we have the survey area which we consider to be the overall population and we now look to provide an estimate relating to haddock abundance in the area excluding the Fundian Channel – Browns Bank AOI under the supposition that it was an actual MPA and thus no tows were allowed to be conducted.

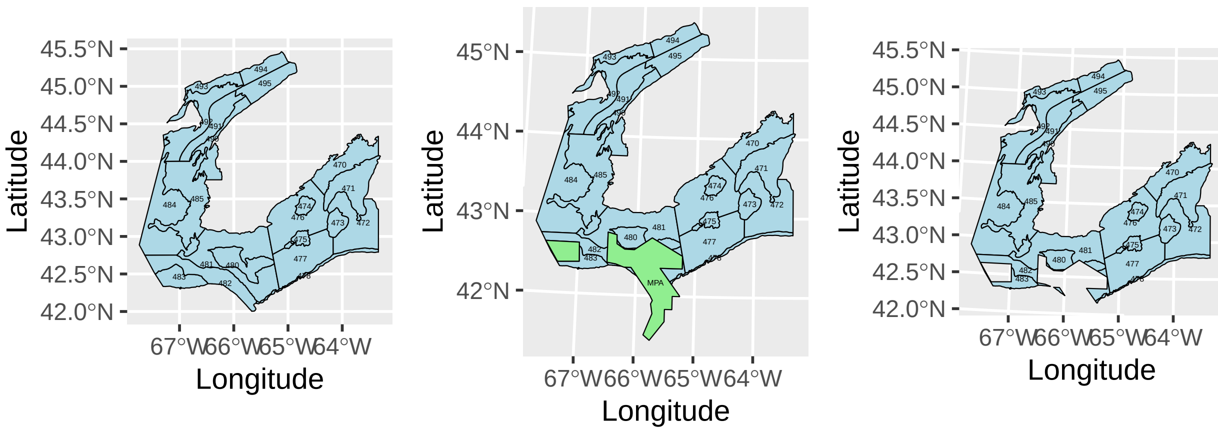

Figure 8: Transition from our original survey area which we consider to be the whole population to the survey area excluding the Fundian Channel – Browns Bank AOI representing our domain of interest

In general, suppose the population $U = \{1, 2, \dots, k, \dots, N\}$ is into D subsets $U_1, U_2, \dots, U_D$ which can be referred to as domains with the size of domain U_d denoted as N_d which yields the following partition:

$$U = \cup_{d=1}^{D} U_d \qquad ; \qquad N = \sum_{d=1}^{D} N_d$$

Our main goal of interest is to estimate a domain specific total

$$t_d = \sum_{U_d} y_k$$

or in our case a domain mean

$$\overline{y}_{U_d} = \frac{t_d}{N_d}$$

for any domain $1, 2, \dots, D$.

We further assume that the survey is carried out over the population U and that a probability sample s with size n_s is drawn from U under a given design such as stratified random sampling. Let s_d be the portion of the sample that falls into a particular domain U_d with size n_{sd}, providing the following partition of the population sample:

$$s = \cup_{d=1}^{D} s_d \qquad ; \qquad n_s = \sum_{d=1}^{D} n_{sd}$$

Pertaining to a stratified random sample, suppose that the population is subdivided into L strata and span the D domains. The domain estimator for a specific domain U_d is then

$$\overline{y}_{U_d} = \frac{\sum_{h=1}^{L} \frac{N_h}{n_h} \sum_{s_{dh}} y_k}{\sum_{h=1}^{L} \frac{N_h}{n_h} n_{s_{dh}}}$$

where s_{dh} is the intersection of domain d and stratum h and $n_{s_{dh}}$ is the size of this sample. The associated variance with the domain mean can be written as

$$Var(\overline{y}_{U_d}) = \frac{1}{\hat{N}_d^2} \sum_{h=1}^{L} N_h^2 \frac{1-f_h}{n_h} \frac{\sum_{s_{dh}} (y_k - \overline{y}_{s_{dh}})^2 + n_{s_{dh}}(1-p_{dh})(\overline{y}_{s_{dh}} - \overline{y}_{U_d})^2}{n_h - 1}$$

where

$$p_{dh} = \frac{n_{s_{dh}}}{n_h} \qquad ; \qquad \hat{N}_d = \sum_{h=1}^{L} N_h (\frac{n_{s_{dh}}}{n_h}) \qquad ; \qquad f_h = \frac{n_h}{N_h}$$

and $\overline{y}_{s_{dh}}$ being the mean of the sample within the domain d and stratum h.

In this case, we can see that we cannot simply re-provide a stratified mean as a means of providing a population indice as we are dealing with a subset of the total survey area and must utilize a domain estimator to preform a similar result.

5.4 Estimating Haddock Abundance in Absense of The AOI

With the tools now to properly provide an estimate for haddock abundance if we opt so ignore the tows preformed within the AOI, we will now proceed with our analysis. The first step in our analysis is to filter out tows that were preformed over the course of the survey and determine how much of an effect this has. Filtering the data based on standardizing the CRS and checking whether a tow's coordinates intersected with the AOI area we find that out of the 3382 tows preformed over the course of 51 years, 383 were conducted in the region, leaving 2999 tows preformed within our modified survey area. This means that of the 3382 samples that had occurred from the overall population pertaining to the original survey area, the domain pertaining to the AOI accounted for 383 of those tows and the domain pertaining to the unaffected area accounted for 2999 tows. In this thesis we are concerned with estimation of the domain concerning the unaffected survey area opposed to the AOI, so we will proceed with the samples obtained within that domain.

With a clearer picture on overall how many tows were lost, we move towards an analysis of the number of tows that were lost within each year. Earlier, we noted that the average number of hauls preformed in any given year is just over 66, and with those tows divided over 21 different strata, the number of hauls associated within any given strata is not that large. Below, we present the yearly number of tows lost to the AOI and its associated proportion of the overall sample. We find that in any given year, on average we expect the proportion of tows lost to be somewhere around 10% which may not seem like a lot but will later find out some strata are affected much worse than others.

Table 13: Yearly count of the number of hauls lost to the Fundian Channel – Browns Bank AOI and the associated proportion of the sample that subsample accounted for

Year	Count	Proportion Lost	Year	Count	Proportion Lost
1970	8	0.18	1996	7	0.1
1971	6	0.14	1997	11	0.16
1972	6	0.12	1998	9	0.13
1973	7	0.14	1999	8	0.12
1974	4	0.08	2000	11	0.16
1975	5	0.1	2001	10	0.14
1976	4	0.08	2002	12	0.16
1977	3	0.06	2003	13	0.15
1978	2	0.04	2004	7	0.11
1979	4	0.08	2005	10	0.14
1980	5	0.1	2006	9	0.11
1981	3	0.06	2007	7	0.1
1982	6	0.11	2008	10	0.13
1983	6	0.12	2009	7	0.09
1984	5	0.1	2010	9	0.12
1985	5	0.09	2011	9	0.1
1986	5	0.1	2012	9	0.11
1987	3	0.04	2013	10	0.12
1988	6	0.08	2014	8	0.11
1989	9	0.13	2015	9	0.11
1990	6	0.08	2016	9	0.1
1991	11	0.16	2017	9	0.1
1992	9	0.13	2018	6	0.08
1993	8	0.11	2019	10	0.11
1994	10	0.14	2020	7	0.1
1995	11	0.16			

Moving on to individual strata in the total survey are one issue that had seemed to have propped up is the lack of an adequate sample size in strata with only 1 tow being preformed in that area. We notice that some strata like 483 had observed a singular tow in a given year and some of its area falls in the AOI so the concern is now to verify if we still manage to retain some tows within a strata or if we have any cases when no information was retained in the strata for that year. Luckily, upon analysis of the survey area, we only will have a limited number of strata where this would be the case however it is important to check as it will affect with how we proceed with providing a domain estimator.

Table 14: Year and Strata where all hauls were preformed in the AOI and thus lost, resulting in no information in that strata for that year

Year	Strata	Year	Strata
1971	482	1985	482
1973	483	1995	483
1973	480	1995	482
1974	483	1997	482
1975	483	1998	482
1976	482	2000	482
1980	482	2004	482
1980	480	2015	483
1981	482	2019	483
1984	482	2020	483

From the table above, we find 20 separate occurrences of losing all hauls to the assumed MPA. This is problematic as we now have no information regarding those strata in those years and will be very difficult to provide an adequate estimate for overall haddock abundance and will require further modifications to our process to provide an estimate. We further note that the strata responsible for these cases are predominately strata 482 & 483, and the years and strata provided here do not always line up with the previous discussion of strata with one haul, implying that multiple hauls are being lost in some cases due to the reduction in towable survey area.

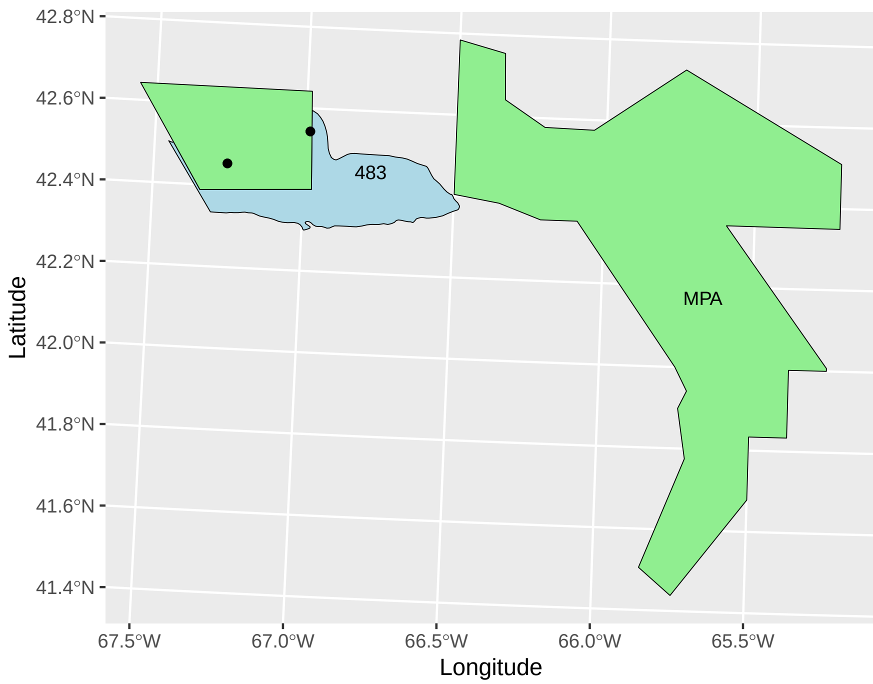

Figure 9: Plot of strata 483 and the Fundian Channel – Browns Bank AOI with the number of tows preformed in that area in 2020, highlighting that multiple tows are being lost in that area

Accumulating the results from our initial investigation of our data and the preceding investigation on the effects of the AOI, we're presented with two glaring issues in regards to providing applicable estimates: the presence of 1 haul within a strata and the issue of no hauls within a strata due to the MPA. The first issue in one haul strata is not as severe as the next, as from analysis of the formulation of the estimate of the domain mean and associated variance, it only becomes an issue when attempting to calculate the variance, as once again we find a denominator of $n_h - 1$. Although not the most ideal situation to be in, for this specific case, we simply have decided to inflate the value of n_h to be 2 instead of 1 and proceed as usual. This inevitably will affect the accuracy of the associated error with the domain mean however luckily does not cause any issues regarding providing an accurate estimate. For our second case the solution is not so clear, with many potential solutions to this issue. The final solution upon proper consultation was to simply introduce an artificial haul within that strata based on the median of the previous years and next years median tow biomass. Note this does not work in all cases as in the final year we also lose all information in regard to strata 483 so we had proceeded in that case to base the artificial tow based on the previous 2 years medians.

We provide our results below based on the above formulations of the domain mean and associated standard error along with our modifications. It is important to note that the *survey* package can be employed to preform a similar analysis, however, has restrictions in regards to sample size within each strata as it does seem to require $n_h > 1$ to adequately provide a calculation which poses major difficulties in our case. Analyzing the following tables and time series, we can see minimal changes in terms of providing a measure of haddock abundance based on the whole survey area versus a survey area with a theoretical MPA, however it is important to reiterate that the methods we have employed to provide a domain estimate for the mean is heavily modified to accommodate missing information and may have resulted in a different conclusion had that not been the case.

Table 15: Table of estimates associated with the domain estimates for the mean and associated standard errors for haddock abundance from 1970 to 2020 with the modifications of artificial tows induced and inflations of the sample sizes in some cases

Year	Mean	SE	Year	Mean	SE
1970	25.78	9.15	1996	53.6	18.13
1971	35.06	11.8	1997	28.84	4.83
1972	15.69	2.27	1998	29.68	6.14
1973	19.79	4.99	1999	32.36	5.11
1974	42.55	12.28	2000	35.41	8
1975	27.42	6.83	2001	50.28	7.04
1976	26.22	3.43	2002	41.29	5.17
1977	150.75	102.65	2003	44.93	21.59
1978	31.49	8.38	2004	25.42	6.31
1979	54.82	11.37	2005	27.52	4.03
1980	59.43	16.43	2006	23.65	3.11
1981	53.77	10.97	2007	34.76	8.39
1982	58.33	17.56	2008	28.64	6.89
1983	31.15	6.58	2009	40.6	9.96
1984	47.05	12.95	2010	28.65	7
1985	53.36	15.69	2011	32.71	12.04
1986	36.21	8.82	2012	19.34	3.64
1987	18.9	3.08	2013	24.91	4.68
1988	18.93	3.02	2014	29.48	4.96
1989	13.15	2.76	2015	43.25	7.02
1990	26.77	4.76	2016	40.05	5.49
1991	39.52	12.18	2017	25.44	2.72
1992	21.07	6.56	2018	29.87	5.02
1993	8.44	1.78	2019	18.42	2.15
1994	14.15	3.12	2020	23.35	3.32
1995	32.29	4.79			

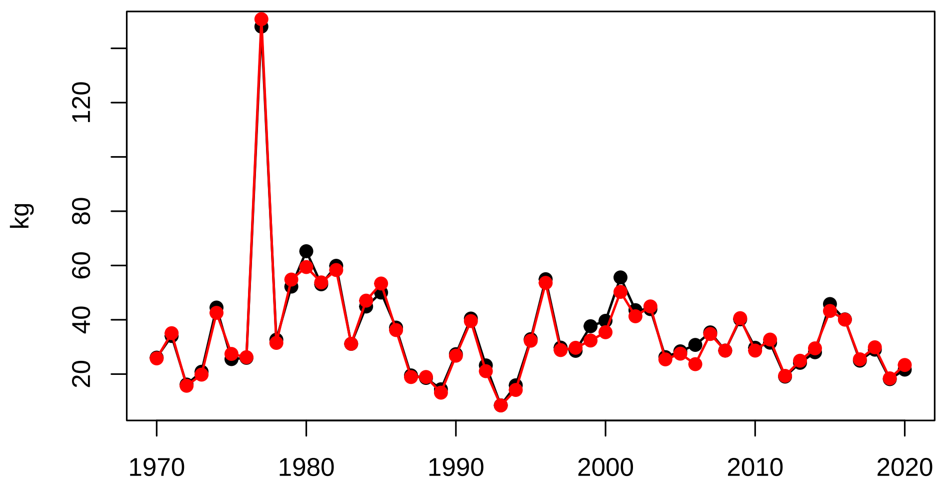

Figure 10: Time series of haddock abundance based on estimates relating to the stratified mean in black associated with the total survey area and the domain mean in red associated with the reduced survey area

6 Closing Remarks

In this thesis, we focused on a design-based assessment of haddock in regards to bottom trawl data obtained through the Summer Research Vessel surveys preformed by the DFO. We first introduced the notion of survey sampling and its underlying goals, more specifically stratified random sampling and the construction of strata. We next apply a design-based inference to provide estimates for the mean catch weight per tow in regards to haddock, providing a measure that can be directly related to the population and in turn provide information regarding trends on abundance. Noting the high stratified mean in the year 1977, we then discuss the impact of unusually large hauls, concluding that they comprise the majority of the stratified mean. Following this, we provide measures of precision regarding our estimates through standard error calculations and interval estimates. With the recent emergence of an AOI within the survey area, we conclude by discussing the implications of an MPA within the survey area which assuming it was in place, reduces the information available to asses the haddock stock and requires an alternative approach in domain estimation to account for these modifications.

Some extensions of this work could include an analysis of model based inferences on the survey, determining whether this avenue can better accommodate the issues highlighted today. Other work could include an assessment of how do we optimally allocate tows across strata, assess the advantages in a stratified sampling design over a simple random sample, or determine whether there is any pattern in the associated stratum with the largest tows observed each year.

Although we have provided a design-based inference for stock assessment, we were overcome with various hurdles that had to be accommodated through various means that have to my knowledge little to no documentation on in regards to low sample sizes and a complete loss of information in some strata under effect of a MPA. This brings up some concerns due to the underlying design of the survey leading to the application of design-based inference in the form of a stratified mean. It is important to note that this problem is not unique, as the costs associated with these surveys can be costly, leading to potential reduction in total tows preformed if the DFO wishes to minimize costs and the rapid increase in protected areas in Canada, which may completely prohibit human acts. With this in mind, it is important to provide a careful assessment on the costs and benefits to researchers in these cases, as today we have shown it has drastically affected our abilities in accurate estimation which may require other methods in response if we wish to continue to monitor the health of a fishery stock.

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