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Relationship between the 4R NAFO division (West coast of Newfoundland) capelin (*Mallotus* spp.) fishery performance index and environmental conditions in the Gulf of St. Lawrence

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Capelin in the Estuary and Gulf of St. Lawrence (GSL) is a stock for which there is currently no abundance index. Science advisories on the status of the capelin stock are therefore based on indirect abundance indices, most notably an index of the commercial fishery performance in NAFO Division 4R. In this study, we test the hypothesis that interannual variations in the commercial fishery performance index would reflect variations in capelin recruitment two years earlier, with the premise that capelin recruitment in the northern GSL is associated with the same oceanographic processes as those demonstrated on the east coast of Newfoundland (NAFO divisions 3KL).

Our analyses showed that the performance index of the 4R Division capelin commercial fishery was strongly related to the same oceanographic processes that determine capelin recruitment on the east coast of Newfoundland, i.e., copepod abundance and bloom timing in the pelagic zone. In addition, the autocorrelation in the performance index had a structure that reflected the longevity of the species, which adds support to the hypothesis. However, the increase in the performance of the commercial capelin fishery from 1993 to 2013 could be explained by other factors that could not be tested, including improvements in the technologies used by commercial fishers. Therefore, it is recommended to continue interpreting the commercial capelin fishery performance index with caution.

INTRODUCTION

Capelin in the Estuary and Gulf of St. Lawrence (GSL) is managed as a single stock under two separate management units, Division 4R and Divisions 4ST of the Northwest Atlantic Fisheries Organization (NAFO, Figure 1), although the population and species structure of capelin in the Estuary and Gulf of St. Lawrence is not clearly defined (Mecklenburg and Steinke 2015, Mecklenburg et al. 2018).

There is currently no research survey to assess the abundance of capelin in the Estuary and Gulf of St. Lawrence. As a result, the latest science advisories (DFO 2008, 2011 and 2013) and updates on the status of Estuary and Gulf of St. Lawrence capelin stock (DFO 2015) were based on indirect stock status indices such as the dispersion index (kriged average of the probability of presence in the bottom trawl of the multidisciplinary groundfish and shrimp survey by Fisheries and Oceans Canada (DFO); Grégoire et al. 2002), commercial landings, commercial fishery performance index and biological indices (male and female lengths, Fulton's condition index) from commercial fishery data.

On the east coast of Newfoundland, a spring research survey specifically designed to estimate capelin biomass is conducted each year (Mowbray 2013 and 2014). In this survey, two-year-old capelin represent on average 58% of the individuals sampled (Mowbray 2014). There is also a larval survey conducted in Trinity Bay (Nakashima and Mowbray 2014). These surveys have demonstrated that cohort strength is determined early in the life cycle and is strongly influenced by environmental conditions (Leggett et al. 1984, Carscadden et al. 2000). More recently, Buren et al. (2014) demonstrated that interannual variations in capelin biomass were explained by a change in the regime of oceanographic conditions (in 1991) and the dynamics of ice retreat, a key determinant of the timing of the spring bloom in the pelagic zone (Wu et al. 2007). Subsequently, Mullowney et al. (2016) proposed a mechanism to explain recruitment strength: the synchronization of capelin larva feeding with spring bloom and the abundance of their zooplankton prey, expressed by the abundance of copepods of the genus *Calanus*. To represent recruitment strength, these authors used the two-year capelin abundance index, which they lagged by two years (i.e., to age 0). They were thus able to test the effect of environmental factors on recruitment. Murphy et al. (2018) also analyzed the factors regulating capelin recruitment and found that, after 1991, capelin was not explained by coastal winds that favoured larval emergence. The age-two abundance index was more related to the density of *Pseudocalanaus sp*. during the larval stage.

In this context, the first objective of our study is to indirectly test the hypothesis that, to some extent, the performance index of the capelin commercial fishery in the Estuary and Gulf of St. Lawrence reflects the abundance of capelin. If the changes in the commercial fishery performance index in Division 4R are related to the same processes regulating capelin abundance on the east coast of Newfoundland (Buren et al. 2014, Mullowney et al. 2016), this would provide some support for the working hypothesis.

The second objective is to describe the methodology used to calculate the various performance indices of the capelin commercial fishery and thus complement the 2018 science advisory (DFO 2018).

MÉTHODS

ZIFF DATA PREPARATION

Landings data for 1986–2017 in NAFO Divisions 4RST were used in this study. These data are compiled by species annually in DFO's ZIFF (Zonal Interchange File Format) databases. Most capelin landings come from a purse and tuck seine fishery on the west coast of Newfoundland (4R). This fishery takes place near the coast and each vessel generally makes one fishing trip per day. We therefore considered that each entry in the database corresponded to one fishing day.

The annual databases were first pooled, resulting in a total of 18,013 entries. Subsequently, the entry of NAFO unit area (example of a unit area: 4Ra) was standardized and the entries with no value for this column were removed. We then selected the entries where the reported fishing gear was the purse seine or the tuck in June, July and August (only two entries in May and September). Finally, entries with missing or unknown vessel length classes were removed if this information could not be found elsewhere in the database using the unique vessel identification number. This last operation resulted in the recovery of 1,012 observations in 4R, for a total of 4,511, and 140 observations in 4T for a total of 157. The length of the vessels is generally proportional to the efficiency of the fishery. Division 4S was not included in the analyses since purse seining and tuck fishing are marginal there (0 to 46 landings per year).

CAPELIN COMMERCIAL FISHERY PERFORMANCE INDICES

A standardized annual catch-per-unit-effort (CPUE) index, which serves as a performance index for commercial fishing, was estimated using multiplicative models (Gavaris 1980) applied to daily CPUE (ln(t/day/boat)). An initial model using the formula below was configured with purse seine and tuck data in 4R, in which all explanatory variables were coded into factors (model 1 in (Table 1):

$$\ln(y_i) = b_0 + b_1x_{i1} + b_2x_{i2} + b_3x_{i3} + b_4x_{i4} + b_5x_{i5} + \varepsilon_i$$

Where y_i: landing (tonne/day)
x_{i1}: year, from 1986 to 2017
x_{i2}: month of the year, where June = 6, July = 7 and August = 8
X_{i3}: length class of vessels where 1 = 1–34.9' (0.30–10.64 m), 2 = 35–44.9' (10.67–13.69 m), 3 = 45–64.9' (13.72–19.78 m), 4 = 65–99.9' (19.81–30.45 m), 5 = 100–124.9' (30.48–38.07 m), and 6 = >125' (38.10 m)
x_{i4}: NAFO Division 4R unit area, 4Ra, 4Rb, 4Rc and 4Rd
x_{i5}: Fishing gear where code 25 means tuck seine and 31 means purse seine
ε_i: Error distributed log-normally

A model including the interaction between year and month (model 2, Table 1) was also configured to test the hypothesis that a change in the timing of capelin spawning could influence the performance of the commercial fishery.

A multiplicative model was also developed for unit area 4Tn (model 3, Table 1). For the latter model, the "GEAR" factor was not included since the purse seine is the only gear used in this area. For models 1 and 3 (Table 1), residuals and Cook's distances were examined to verify whether the application conditions were met.

Two other multiplicative models were configured to visualize the effect of the arrival of the tuck seine in 2005 on the commercial fishery performance index in 4R: a model for the purse seine and a model for the tuck seine (models 4 and 5, Table 1).

The standardized CPUEs were produced using, for each year, the values predicted by the models for the following levels of standardization factors: June, length class 2, unit area 4Rc and purse seine. The estimated marginal means calculated using the “emmeans” function of the R library of the same name (Lenth 2018) are also presented for model 1.

ENVIRONMENTAL DESCRIPTORS

Environmental conditions in the GSL were described using four physical descriptors with the potential to affect the dynamics of phytoplankton spring bloom in the pelagic zone (Mullowney et al. 2016). The descriptors, from Galbraith et al. (2018), are the spring timing of sea surface temperature warming, the maximum ice volume in the GSL, the date of the last ice occurrence in the Esquiman Channel area (Region 5, Galbraith et al. 2018) and the sum of cold intermediate layer anomalies and ice indicators (Table 2).

Variations in biological conditions were described using zooplankton abundance data collected at a station off the coast of Rimouski, the longest series of zooplankton available in the GSL (1992–2015). This station is located in the St. Lawrence Estuary and is sampled on an almost weekly basis from spring to late fall. Interannual variations in the abundance indices of the main zooplankton species at this station are generally consistent with those of other Gulf regions (Plourde et al. 2014). Two types of biological indices were used: annual averages of abundance for the three dominant copepod species (*Calanus finmarchicus*, *C. glacialis* and *C. hyperboreus*), three indices to quantify changes in copepod phenology using *C. finmarchicus*, the dominant copepod species. These last three descriptors are the time when the maximum abundance of 1st- and 2nd-generation young stages (c1–c3) is observed (cf_Timing_max_C1.3_G1 and cf_Timing_max_C1.3_G1 respectively), as well as the proportion of these stages in the population (Cf_G2G1_maxC1.3; Plourde et al. 2015). Abbreviations for each of the environmental descriptors are provided in Table 2.

RELATIONSHIPS BETWEEN THE SEINE FISHING PERFORMANCE INDEX AND ENVIRONMENTAL CONDITIONS

Subsequent analyses were conducted on the capelin commercial fishery performance index in 4R lagged by two years (PI_{t-2}) using the predicted values from Model 1 (Table 1) for the standard levels mentioned above. This two-year lagged performance index (PI_{t-2}) was related to environmental descriptors representing the same processes regulating capelin abundance on the east coast of Newfoundland.

All independent variables were standardized (mean of 0, standard deviation of 1) before the analyses, so that the absolute values of the regression coefficients could be directly interpreted in terms of the relative importance of the explanatory variables in the model (Legendre and Legendre 2012). The performance index for 4Tn could not be used for subsequent analyses because the series was not long enough.

Variance inflation factors (VIFs) were calculated to identify the colinear variables and remove them before starting the analyses. The variable representing the sum of the cold intermediate layer anomalies and ice indicators were removed so that no VIF was greater than 5 (Zuur et al. 2011) (Table 2).

The autocorrelation in the detrended data was then visually inspected. Since the data had a strong temporal autocorrelation pattern, linear regression models with all explanatory variables and different autocorrelated error structures (generalized least squares method) were compared using the corrected Akaike information criterion (AICc) corrected for small samples (Burnham and Anderson 2003). The types of autocorrelated error structures considered are: compound symmetry, first-order autoregressive (AR-1), as well as autoregressive moving average (ARMA) with all combinations of the following values of p (number of autoregressive parameters) and q (number of parameters for the moving average): 0, 1 or 2.

Subsequently, a backward selection of explanatory variables was carried out on the basis of the AICs. Residuals, autocorrelation in the residuals and Cook's distances of the best model were examined to ensure that the application conditions were met.

The same analyses were also performed with the 4R performance index lagged by one and three years.

RELATIONSHIPS BETWEEN THE CAPELIN COMMERCIAL FISHERY PERFORMANCE INDEX (4R) AND DISPERSION INDICES

The dispersion index of capelin corresponds to its probability of presence (annual average) in the bottom trawl of the DFO multidisciplinary groundfish and shrimp survey in the northern Gulf. The probability is obtained by kriging and the methodology is described in Grégoire et al. (2002).

The relationship between the capelin commercial fishery performance index in 4R and the dispersion index for the same area was tested with the Pearson correlation coefficient test. The test was also performed with the dispersion index for 4RST. The dispersion index was available from 1990 to 2017 and from 1990 to 2013 for 4R and 4RST respectively.

All data manipulations and analyses were performed in R (R Core Team 2018).

RESULTS

PERFORMANCE INDICES

The standardization analysis carried out on the CPUE (ln(t/day)) of the purse seiners in Division 4R was significant (ANOVA, $F = 71.64$, $p < 0.001$) as was the contribution of each of the factors of the model ($p < 0.01$) (Table 3) (see also Grégoire and Bruneau 2012). The model explains 39.1% of the total variance. Residuals (Figure 2A) and standardized residuals (Figure 2B) do not have a pattern indicating a violation of variance homogeneity. The residuals follow a distribution that deviates slightly from normal (Figure 2C) and do not have extreme values that can influence the model (all Cook's distances are less than 0.5, Figure 2D). Fishing is increasingly efficient as the season progresses (monthly effect), is more efficient for the large vessels length classes (LENG_CL 4, 5 and 6) and NAFO unit areas further south (U_AREA 4Rc and 4Rd), and the performance of the purse seine is higher than that of the tuck seine (Figure 3). The model performance index as described by the standardized means was calculated by setting the factors at the following levels: MONTH = 6, LENG_CL = 2, U_AREA = 4Rc and GEAR = 31. The index shows an average increase of 2.71 t/d/year from 2005 to 2013. Since 2014, the annual values of this index have been declining, but remain above the series average (Figure 4). The index as calculated from the estimated marginal means (Figure 5) has the same pattern as that calculated with predetermined levels since it comes from the same model. However, the range of values of the two indices is different, as marginal means are estimated from the average effect of each factor while standardized means are estimated for predetermined levels of factors.

The interaction between year and month (model 2, Table 1) was significant, ($p < 0.0001$). This model explained 42.4% of the variance, 1.3% more than model 1.

The analysis of variance performed on the CPUE of purse seiners in unit area 4Tn was also significant ($F = 2.821$, $p < 0.01$) as was the contribution of each of the factors of the model (p <

0.05), with the exception of the vessel length class ($p > 0.05$) (Table 4). The model explains 14.7% of the total variance and the residuals (Figure 6A) and standardized residuals (Figure 6B) have patterns that could suggest a violation of homogeneity of variances. The residuals follow a distribution that deviates from normal (Figure 6C) and do not have extreme values that can influence the model (all Cook's distances are less than 0.5) (Figure 6D). In 4Tn, performance is higher in June and comparable for the different vessel length classes (Figure 7). Although the standardization factors are not exactly the same, the average performances measured in 4R and 4Tn are similar. However, the performance measured in 4Tn has more variability (Figure 8).

The arrival of tuck seine fishing in 4R in 2005 seems to have a negligible effect on the overall performance index (purse seine and tuck) since the index for purse seine and tuck seine vary consistently (Figure 9).

RELATIONSHIP BETWEEN THE PERFORMANCE INDEX AND ENVIRONMENTAL CONDITIONS

The collinearity of the environmental descriptors related to PI_{t-2} was not severe since all VIFs were below 5 (Neter et al. 1996, Chatterjee et al. 2000; Table 2). The autocorrelation in the commercial fishery performance index in 4R was significant for a lag of one, two and three years and shows a decreasing general pattern (Figure 10).

Models with different autocorrelated error structures linking PI_{t-2} and all environmental descriptors were compared on the basis of AICc (Table 5). The model with the most support is the one involving a normally-distributed and non-autocorrelated error. It is also the model with the lowest number of parameters (K). It was therefore selected for the subsequent analysis, which consisted of backward selection of explanatory variables based on the AICs.

The optimal model selected includes the timing of spring warming, the maximum winter ice volume and the average annual abundance of *C. hyperboreus* and *C. glacialis* (Table 6). The model was significant ($p < 0.0001$) and explains 72.2% of the change in the PI_{t-2}. Residuals (Figure 11A) and standardized residuals (Figure 11B) do not have a pattern indicating a violation of variance homogeneity. The residuals are normally distributed (Figure 11C), do not have extreme values that can influence the model (all Cook's distances are less than 0.5) (Figure 11D) and are not significantly autocorrelated ($r = 0.43$, $p = 0.052$ for a lag of 1). A comparison of the values predicted by the environmental model and the 4R performance index, ordered by year, is also presented in Figure 12 and shows that the predictions correspond very well with the observed values.

The mean annual abundance of *C. hyperboreus* is the most important variable contributing to the model, followed by the maximum volume of ice, and the timing of spring warming. The positive regression coefficient of *C. hyperboreus* means that an increase in abundance of this species is followed, two years later, by an increase in the performance of the commercial capelin fishery in NAFO Division 4R. Similarly, an increase in the maximum ice volume and a later spring warming are associated with increases in fishing performance two years later. The average annual abundance of *C. glacialis* is of less importance in the model (Table 6).

The same analyses performed with the 4R performance index lagged one and three years yielded very similar results except for the fact that the best models were slightly less well adjusted to the data than with a lag of two years.

RELATIONSHIPS BETWEEN THE FISHING PERFORMANCE INDEX AND THE DISPERSION INDICES

The correlation between the commercial fishing performance index in 4R and the dispersion index for the same area was insignificant at the threshold $\alpha = 0.05$ ($r = 0.355$, $p = 0.08147$; Figure 13). The correlation between the performance index in 4R and the dispersion index in the 4RST divisions was significant ($r = 0.53$, $p = 0.009$; Figure 14).

DISCUSSION

Multiplicative models applied to CPUEs have produced standardized capelin commercial fishery performance indices for each year in NAFO Division 4R and unit area 4Tn. These indices are called "standardized" because they take into account interannual variations in the date of landings (months), the length of vessels, unit areas (4Ra to 4Rd), as well as the type of gear used. These indices are therefore directly comparable from one year to the next.

The 4R capelin commercial fishery performance index lagged by two years is very well explained by environmental indices reflecting the same processes suggested as fundamental in controlling capelin recruitment on the east coast of Newfoundland (Buren et al. 2014, Mullowney et al. 2016). In addition, the structure of the autocorrelation in the detrended index corresponds to the longevity of spawning adults in the catchable population. The significant autocorrelation at a time lag of one and two years could be explained by the fact that most females reproduce twice in their lifetime or, to a lesser extent, three times. This reinforces the idea that, to some extent, the fishing performance index represents a relative index of capelin recruitment two years earlier.

The strong correlation between PI_{t-2} and the annual mean abundance of *C. hyperboreus* suggests a strong relationship, but the underlying mechanism remains hypothetical. The latter could be related to the importance of spring feeding to the condition of juveniles and adults, as well as to gonad development (Gerasimova 1994). *C. hyperboreus* is an important copepod in deep-water zooplankton communities in the GSL (Plourde et al. 2002, Plourde et al. 2003). It is an important prey for juvenile and adult capelin (Vesin et al. 1981), but capelin larvae (< 75 mm) do not feed on such large copepods (Vesin et *al.* 1981, Courtois and Dodson 1986, O'Driscoll et al. 2001). Gerasimova (1994) reports that in spring, *C. hyperboreus* was the most important prey of juvenile capelin at a time when copepods were most dominant in their diet. The capelin wintering habitat, according to studies on the east coast and the Grand Banks of Newfoundland, is deep water (150–250 m) in bays (Winters 1970) or on the slopes of the continental shelf (Kovalyov and Kudrin 1973). The average annual abundance of *C. hyperboreus* measured at the Rimouski station shows an increasing trend from 1995 to 2015, but greater variability in the data is observed from 2003 onwards. The habitat of juvenile and adult capelin in winter and spring, as well as the consumption of *C. hyperboreus* by the latter, could therefore explain the strong relationship between PI_{t-2} and this copepod.

The performance index for capelin fishing in 4R was either not significantly correlated or very weakly correlated with the dispersion indices calculated from the multidisciplinary groundfish and shrimp survey. These results, combined with studies showing that several pelagic fish species have changed their vertical distribution based on the absence of predators in the demersal zone (Mowbray 2002, McQuinn 2009), reinforce the idea that data from groundfish surveys do not reflect fluctuations in the abundance of pelagic fish populations.

The use of a commercial fishing performance index as an indicator of stock status is based, among other things, on the premise that the catchability of fish by fishers remains constant over time. However, many factors, such as biological and environmental, socio-economic and technological factors, are likely to influence catchability. Biological and environmental factors include the behaviour of capelin, which may vary from year to year. Indeed, the catchability of capelin by commercial fishers could be influenced by the selection of the spawning habitat (demersal vs. seashore), which would appear to be determined by water temperature (Crook et al. 2017). Similarly, a change in the vertical and spatial distribution of capelin from one year to the next could influence its catchability (Campbell 2004). The timing of spawning could also affect the performance of the commercial fishery. The latter factor was statistically tested by adding the YEAR * MONTH interaction in the 4R multiplicative model (model 2, Table 1). This new term, although significant, did not improve Model 1 in a biologically significant way. In addition, the genetic structure of the capelin stock fished in the GSL is not well known (DFO 2018) and it is possible that part of the fishery targets capelin from Labrador.. The fishing performance index could therefore be influenced by the intrusion of capelin through the Strait of Belle Isle in some years, adding uncertainty to its interpretation.

Socio-economic factors could also influence the performance of commercial fishing, since the profitability of the activity influences fishers' behavior, including their likelihood of taking risks (Holland 2008) and their movement patterns in the fishing area (Gillis 2003). According to Lam et al. (2011), the two main expenses of fishers in North America are wages and fuel. In Appendix 1, we assumed that wages were constant from year to year (taking into account inflation) and compared the effect of fuel costs and capelin selling prices (in constant dollars) to the environmental model. The two economic factors and the environmental descriptors of the best model jointly accounted for 33.7% of the variation, but the economic factors did not provide any new information in the model. The hypothesis that the performance of commercial fishing is influenced by economic factors is therefore poorly supported, according to the available data.

Technological advances could also explain the increase in commercial fishing performance from 2004 to 2013. In particular, increasing vessel power, improvements of depth sounders, inexpensive bathymetric charts combined with GPS navigation systems that make navigation possible at all times, as well as electronic communications that can increase cooperation, and even radars that can identify seabird aggregations are all examples of technologies that influence catchability and make fishing more efficient (Rahikainen and Kuikka 2002). In the case of the 4R commercial fishery, it was not possible to test the influence of these factors.

CONCLUSION

The capelin commercial fishery performance index in 4R lagged by two years was very well explained by variables reflecting the processes underlying the recruitment of the same species on the east coast of Newfoundland. Similarly, the temporal autocorrelation in the detrended index shows a pattern consistent with the biology of the species. These two elements support the hypothesis that the capelin performance index in Division 4R, to some extent, reflects a relative recruitment index two years earlier. However, it must be interpreted with caution since many factors that are not taken into account in the standardization model could influence the performance index. There are also several examples that show that the performance of commercial fisheries can remain stable despite declining populations, including northern Atlantic cod (Rose and Kulka 1999), as well as several species of gadiforms and flatfish in European waters (Harley et al. 2001). It will be interesting to test the capelin environmental model with new years of data.

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TABLES

Table 1: Multiplicative models used to produce standardized performance indices for the capelin commercial fishery in NAFO Divisions 4R and 4T. Leng CL.: vessel length class.

		Standardization factors						
Num	Model	Year	Month	Length Cl.	Unit Area	Fishing gear	Year*Month	Data
1	4R	X	X	X	X	X	-	4R
2	4R interaction	X	X	X	X	X	X	4R
3	4Tn	X	X	X	-	-	-	4T
4	4R purse	X	X	X	X	-	-	4R purse seine
5	4R "tuck"	X	X	X	X	-	-	4R "tuck" seine

Table 2: Abbreviations, definitions and variance inflation factors (VIFs) of environmental descriptors related to the commercial fishery performance index lagged two years in 4R.

Abbreviation	Definition	VIF
SprTiming	Timing of spring warming (Julian day)	1.13
GSL_Ice_Volmax	Maximum volume of ice	3.55
Day_lastIce_Reg5	Sum of cold anomalies CIL and ice	2.10
Cfin	*Calanus finmarchicus* (mean an. ab.)	1.52
Cglac	*Calanus glacialis* (mean an. ab.)	1.66
Chyp	*Calanus hyperboreus* (mean an. ab.)	1.38
Cf_Timing_max_C1.3_G1	Timing of the max. abundance of young stages (C1C3), 1st generation.	2.09
Cf_Timing_max_C1.3_G2	Timing of the max. abundance of young stages (C1C3), 2nd generation	1.61
Cf_G2G1_maxC1.3	Ratio G2 on G1 (2nd/1st generation)	1.78

Table 3. Results of the multiplicative model used to standardize the CPUE (performance index) of capelin in purse and tuck seine commercial fishery in NAFO Division 4R. The following abbreviations are used: df, degree of freedom; SC, sum of squares; Pr, probability; Std. Dev, standard deviation; S-E., standard error.

ANOVA table	df	SS	F	Pr(>F)	
YEAR	30.0	617.95	30.371	< 2e-16	***
MONTH	2.0	9.37	6.909	0.001	**
LENGTH_CL	5.0	1181.91	348.531	< 2e-16	***
UNIT_AREA	3.0	73.38	36.066	< 2e-16	***
FISH_GEAR	1.0	109.59	161.590	< 2e-16	***
Residuals	3028.3	4454	-	-	-
Signif, : 0 *** 0.001 ** 0.01 * 0.05					

Model:	lpue ~ YEAR + MONTH + UNIT_AREA + LENGHT_CL				
Residuals:	Min,	1Q	Median	3Q	Max.
	-8.6049	-0.3248	0.1137	0.5018	1.9518
Coefficients:	Estimate	SE	Value t	Pr(>|t|)	-
intercept	0.936	0.125	7.457	0.000	***
YEAR1987	-0.028	0.187	-0.151	0.880	-
YEAR1988	0.493	0.591	0.835	0.404	-
YEAR1989	1.075	0.264	4.073	0.000	***
YEAR1990	0.364	0.246	1.480	0.139	-
YEAR1991	0.821	0.119	6.877	0.000	***
YEAR1992	0.477	0.109	4.376	0.000	***
YEAR1993	0.381	0.114	3.337	0.001	***
YEAR1994	0.070	0.187	0.373	0.709	-
YEAR1996	-0.043	0.105	-0.410	0.682	-
YEAR1997	0.093	0.107	0.872	0.383	-
YEAR1998	0.564	0.109	5.157	0.000	***
YEAR1999	0.454	0.115	3.945	0.000	***
YEAR2000	0.458	0.115	3.978	0.000	***
YEAR2001	0.546	0.212	2.581	0.010	**
YEAR2002	0.557	0.122	4.580	0.000	***
YEAR2003	0.528	0.116	4.537	0.000	***
YEAR2004	0.405	0.112	3.599	0.000	***
YEAR2005	0.575	0.110	5.227	0.000	***
YEAR2006	0.889	0.109	8.190	0.000	***
YEAR2007	0.781	0.117	6.668	0.000	***
YEAR2008	0.991	0.116	8.528	< 2e-16	***
YEAR2009	0.986	0.111	8.853	< 2e-16	***
YEAR2010	1.288	0.115	11.154	< 2e-16	***
YEAR2011	1.345	0.118	11.365	< 2e-16	***
YEAR2012	1.138	0.113	10.080	< 2e-16	***
YEAR2013	1.521	0.126	12.117	< 2e-16	***
YEAR2014	1.454	0.126	11.522	< 2e-16	***
YEAR2015	1.380	0.111	12.417	< 2e-16	***
YEAR2016	1.276	0.115	11.127	< 2e-16	***
YEAR2017	1.086	0.161	6.768	0.000	***
MONTH7	0.198	0.044	4.520	0.000	***
MONTH8	0.290	0.217	1.339	0.181	-
LENGTH_CL2	0.379	0.081	4.671	0.000	***
LENGTH_CL3	0.657	0.084	7.778	0.000	***
LENGTH_CL4	1.510	0.088	17.231	< 2e-16	***
LENGTH_CL5	1.598	0.090	17.821	< 2e-16	***
LENGTH_CL6	1.536	0.107	14.385	< 2e-16	***
UNIT_AREA4Rb	0.171	0.049	3.515	0.000	***
NIT_AREA4Rc	0.396	0.046	8.539	< 2e-16	***
NIT_AREA4Rd	0.375	0.066	5.654	0.000	***
FISH_GEAR31	0.511	0.040	12.712	< 2e-16	***

Model:	lpue ~ YEAR + MONTH + UNIT_AREA + LENGHT_CL				
Residuals:	Min,	1Q	Median	3Q	Max.
	-8.6049	-0.3248	0.1137	0.5018	1.9518
SE residuals: 0.8235 on 4469 dl.					
Multiple R^2: 0.3966, Adjusted R^2: 0.3911					
F: 71.64 on 41 and 4469 dl, p: <2.2E-16					

Table 4. Results of the multiplicative model used to standardize capelin CPUE (performance index) for the commercial purse seine fishery in the 4Tn unit area. The following abbreviations are used: df, degree of freedom; SS, sum of squares; Pr, probability; S-E., standard error.

ANOVA table	df	SS	F	Pr(>F)	
YEAR	10.0	136,93	2,741	0,0042	**
MONTH	1.0	30,50	6,107	0,0147	*
LENGTH_CL	3.0	29,82	1,990	0,1185	-
Residuals	134.0	669,36	-	-	-
Signif. 0 *** 0.001 ** 0.01 * 0.05					

Model:	lpue ~ YEAR + MONTH + UNIT_AREA + LENGTH_CL					
Residues:	Min.	1Q	Median	3Q		Max
	-6.7789	-0,3572	0,4895	1,1803		3,6469
Coefficients:	Estimate	SD	Value t	Pr(>|t|)	-	
Intercept	0.229	3,284	0,070	0,945	-	
YEAR1993	-1.058	3,799	-0,279	0,781	-	
YEAR2006	-0.234	1,867	-0,125	0,901	-	
YEAR2007	0.152	2,296	0,066	0,947	-	
YEAR2008	-1.071	2,787	-0,384	0,701	-	
YEAR2009	-2.185	1,706	-1,281	0,202	-	
YEAR2010	-1.070	1,718	-0,623	0,535	-	
YEAR2011	-0.789	1,672	-0,472	0,638	-	
YEAR2012	-0.608	2,107	-0,289	0,773	-	
YEAR2015	-0.590	1,899	-0,311	0,757	-	
YEAR2016	-0.717	1,824	-0,393	0,695	-	
MONTH6	3.300	1,161	2,842	0,005	**	
LENGTH_CL23	-0.351	2,628	-0,134	0,894	-	
LENGTH_CL24	0.830	2,581	0,322	0,748	-	
LENGTH_CL25	1.262	2,786	0,453	0,651	-	
SE residuals: 2.235 on 134 df						
Multiple R^2: 0.2276, Adjusted R^2: 0.1469						
F: 2.821 on 14 and 134 df, p: 0.001004						

Table 5. Comparison of different autocorrelated error structures for models linking the capelin fishery performance index lagged by two years to all environmental descriptors. K: number of parameters.

Model	K	AICc
No temporal autocorrelation	11	97.28
Compound Symmetry	12	106.48
Auto-regressive order 1 (AR-1)	12	99.33
ARMA: $p = 1$, $q = 0$	12	99.10
ARMA: $p = 0$, $q = 1$	12	101.67
ARMA: $p = 1$, $q = 1$	13	110.28
ARMA: $p = 2$, $q = 0$	13	110.28
ARMA: $p = 0$, $q = 2$	13	112.25
ARMA: $p = 2$, $q = 1$	14	124.33
ARMA: $p = 1$, $q = 2$	14	124.33
ARMA: $p = 2$, $q = 2$	15	141.75

Table 6. Results of the optimal multiple linear regression model between PI_{t-2} and the environmental descriptors. The following abbreviations are used: df, degree of freedom; Pr, probability; S-E, standard error.

Model:	IP_{t-2} ~ SprTiming + GSL_Ice_Volmax + Cglac + Chyp				
Residues:	Min.	1Q	Median	3Q	Max
	-0.9107	-0.2506	0.0101	0.1954	1.1010
Coefficients:	Estimate	SD	Value t	Pr(>|t|)	-
Intercept	-0.052	0.110	-0.467	0.646	-
SprTiming	0.249	0.113	2.200	0.041	*
GSL_Ice_Volmax	0.276	0.130	2.118	0.048	*
Cglac	-0.179	0.121	-1.488	0.154	-
Chyp	0.690	0.113	6.080	0.000	***
SD residuals: 0.572 on 18 dl					
Multipe R^2: 0.773, Adjusted R^2: 0.722					
F: 15.29 on 4 and 18 df, p: 1.294e-05					

FIGURES

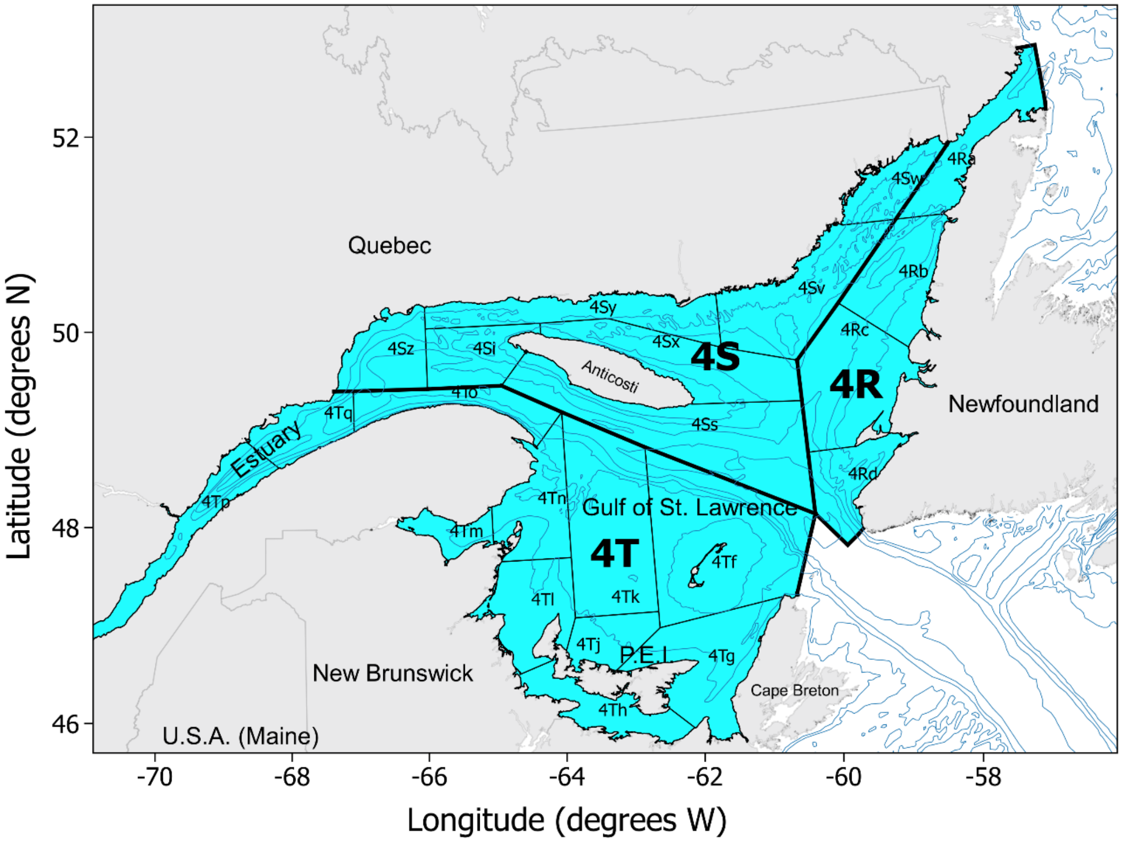

Figure 1. Map of the 4RST NAFO Divisions and unit areas of the Estuary and Gulf of St. Lawrence.

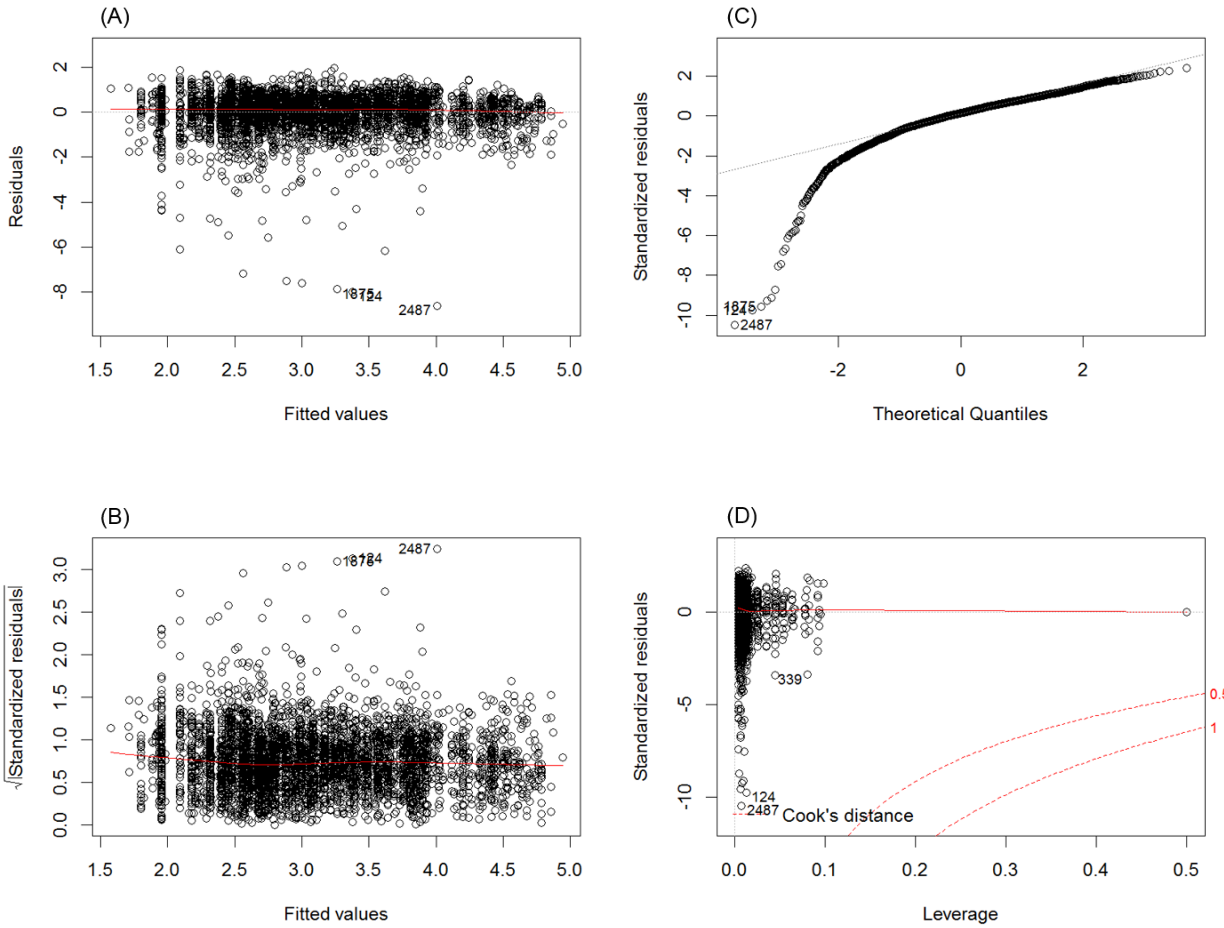

Figure 2. Diagnostics of the multiplicative model used to standardize the capelin CPUE (performance index) in purse and tuck seine fishery in NAFO Division 4R. (A: residuals vs fitted values of the model, B: square root of the absolute values of the standardized residuals vs fitted values of the model, C: quantile-quantile graph of the standardized residuals and D: standardized residuals vs. leverage graph and Cook's distances of 0.5 and 1).

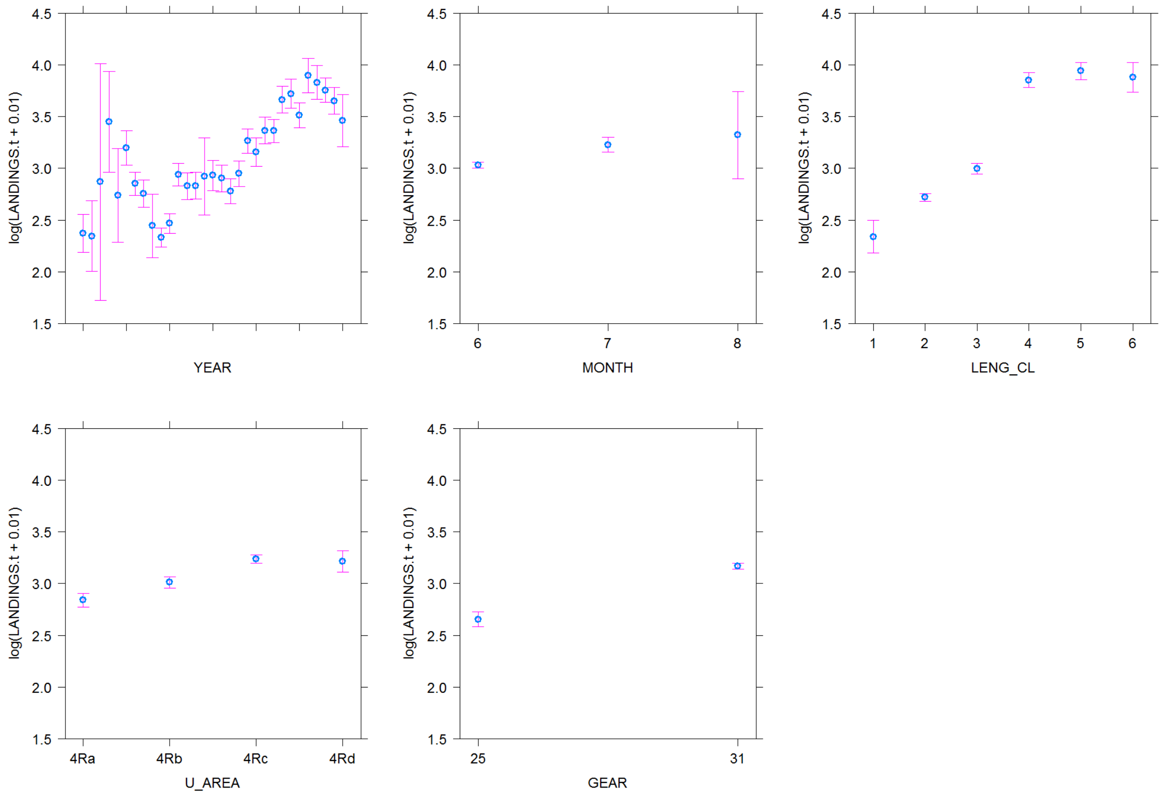

Figure 3. Effects and standard errors of the different levels of standardization factors on the performance index for the NAFO Division 4R commercial capelin fishery. The y-axes are expressed on the linear predictor scale.

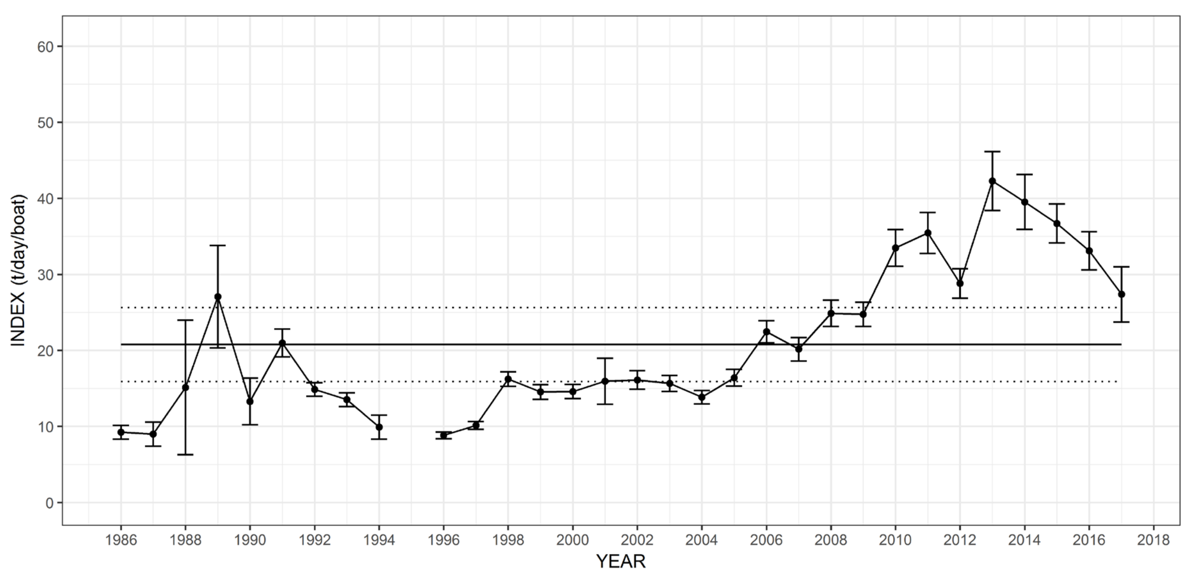

Figure 4. Performance (t/day/boat) of the purse and tuck seine fishery on the west coast of Newfoundland (NAFO Division 4R) as measured by a standardized catch-per-unit-effort index. The reference levels used in standardization are: MONTH = 6, LENG_CL=2, U_AREA = 4Rc and GEAR=31. The solid horizontal line represents the mean of the series and the dotted lines the mean ± 0.5 standard deviation.

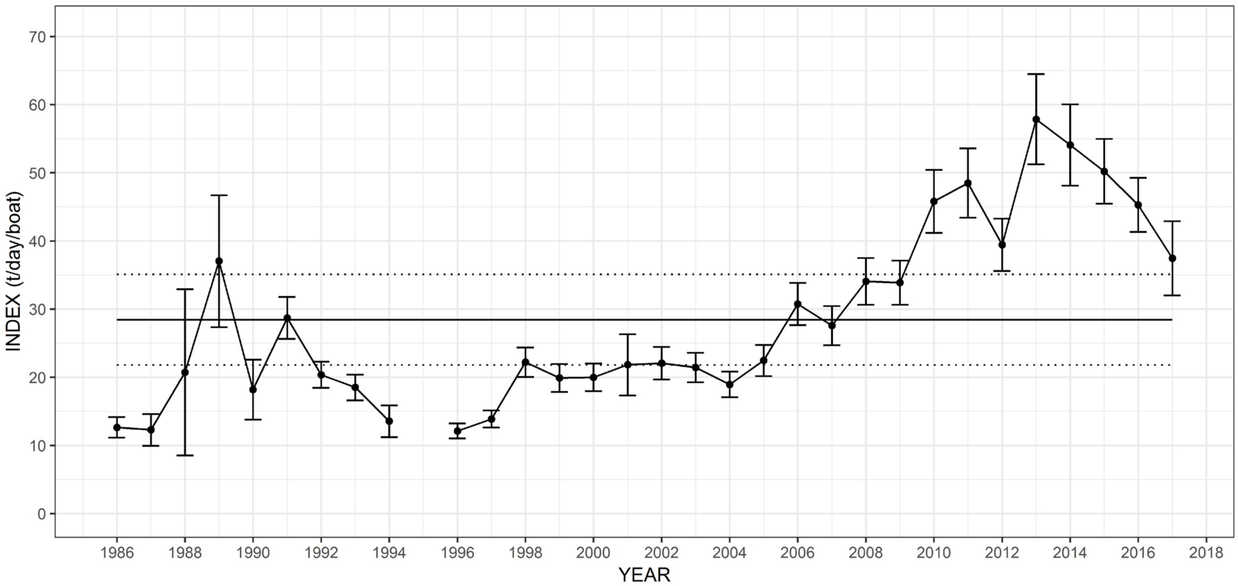

Figure 5. Performance (t/day/boat) of the purse and tuck seine fishery on the west coast of Newfoundland (NAFO Division 4R) as measured by a standardized catch-per-unit-effort index (estimated marginal means). The solid horizontal line represents the mean of the series and the dotted lines the mean ± 0.5 standard deviation.

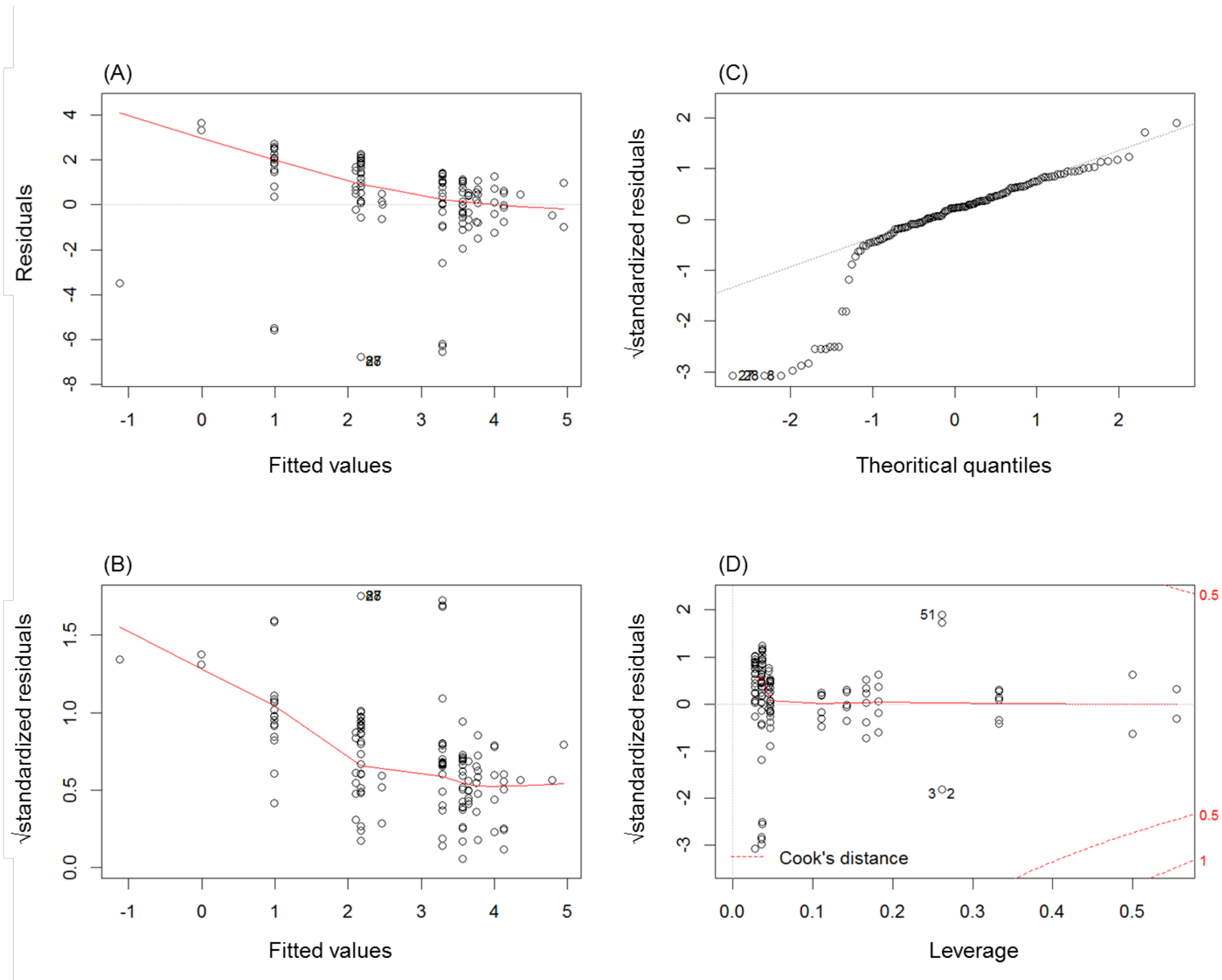

Figure 6. Diagnostics of the multiplicative model used to standardize the capelin CPUEs (performance index) of the purse seine fishery in unit area 4Tn (A: residuals vs fitted values of the model, B: square root of the absolute values of the standardized residuals vs fitted values of the model, C: quantile-quantile graph of the standardized residuals and D: standardized residuals vs. leverage graph and Cook's distances of 0.5 and 1).

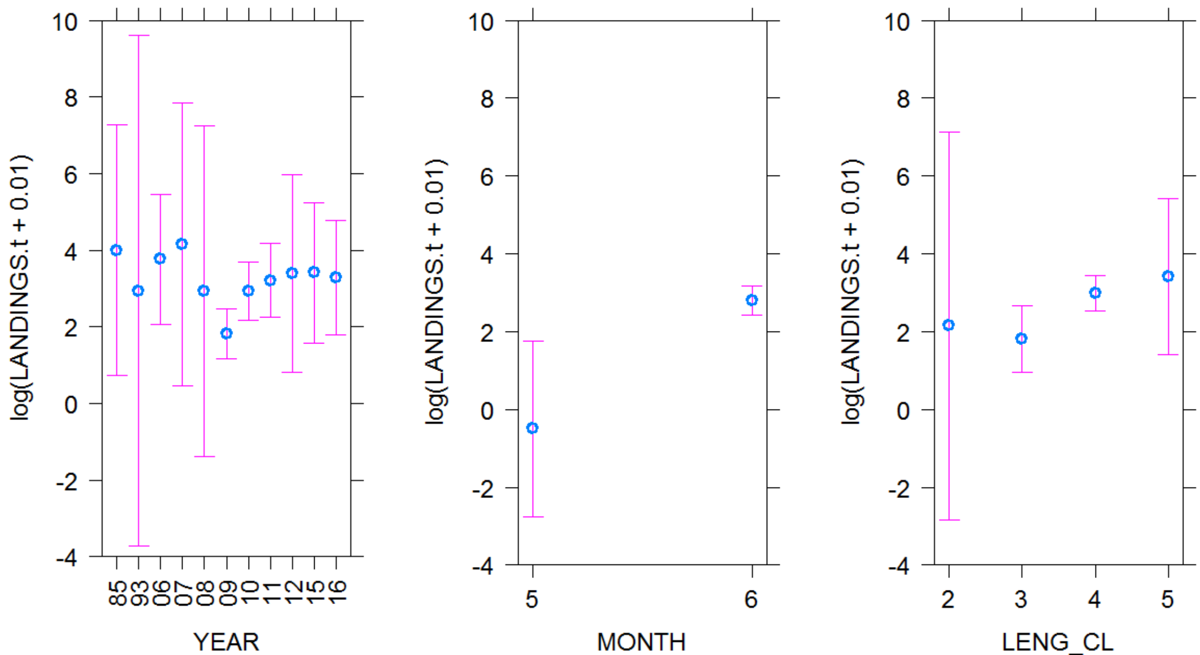

Figure 7. Effects and standard errors associated with the different levels of standardization factors on the performance index for the capelin commercial fishery in unit area 4Tn. The y-axes are expressed on the linear predictor scale.

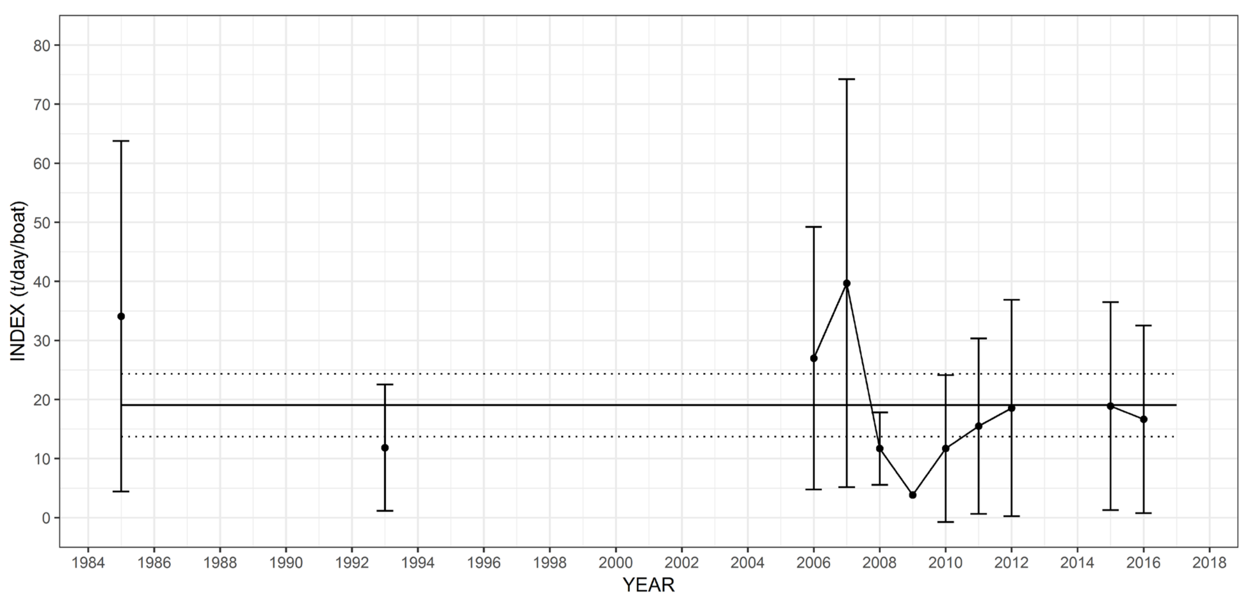

Figure 8. Performance (t/day/year) of purse seine fishery in unit area 4Tn as measured by a standardized catch-per-unit-effort index. The solid horizontal line represents the mean of the series and the dotted lines represent the mean ± 0.5 standard deviation. The reference levels used in standardization are: MONTH=6, LENG_CL = 2.

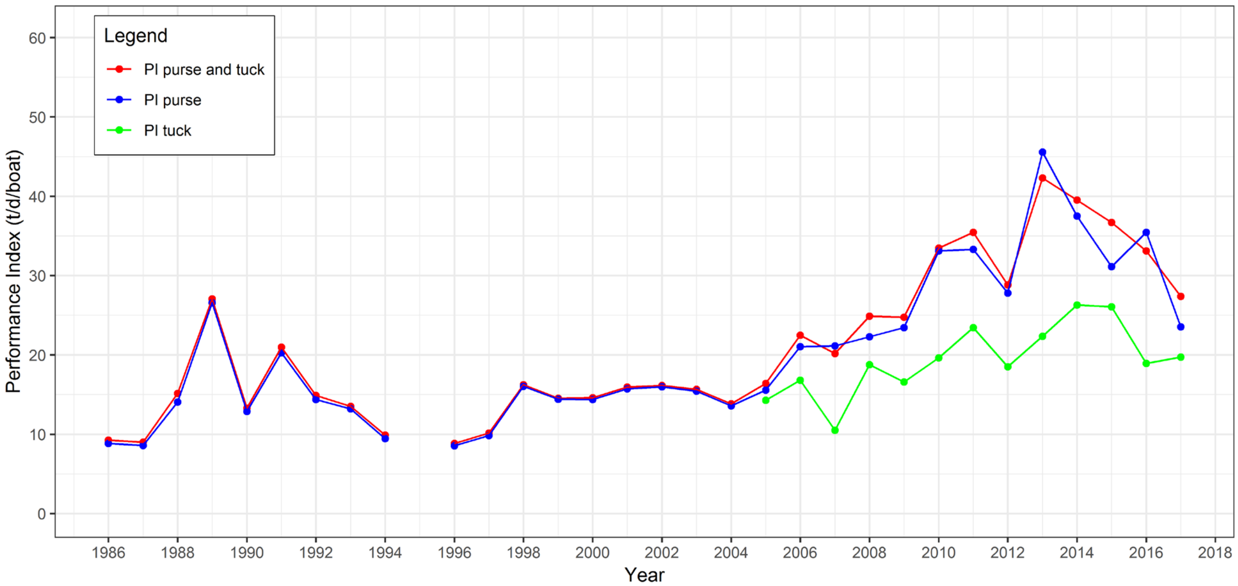

Figure 9. Comparison between purse, combined purse and tuck, and tuck seine fishery performance indices (models 1, 4 and 5 in Table 1: Multiplicative models used to produce standardized performance indices for the capelin commercial fishery in NAFO Divisions 4R and 4T. Leng CL.: vessel length class) for NAFO Division 4R.

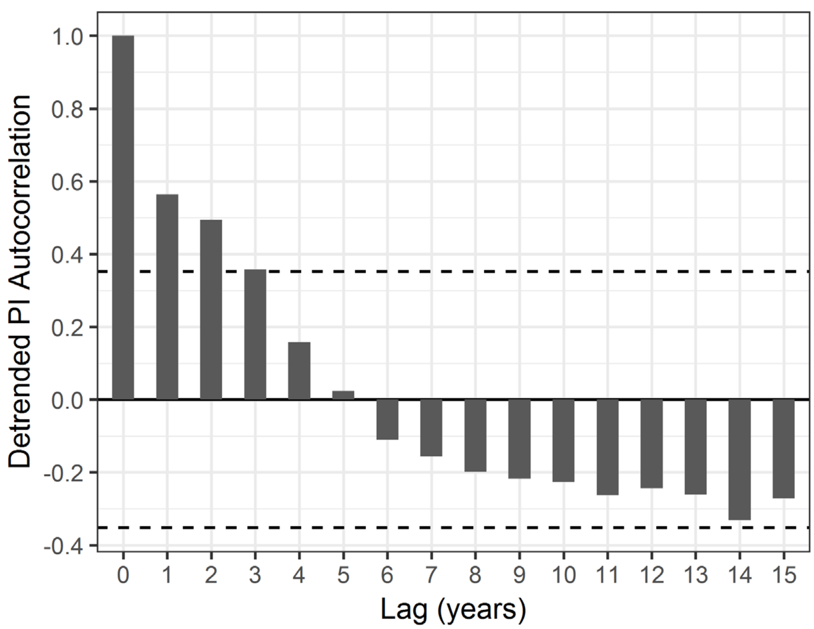

Figure 10. Autocorrelation in the detrended commercial fishery performance index as a function of the lag of the time series with itself (years). The horizontal dotted lines represent the threshold at which autocorrelation is significant.

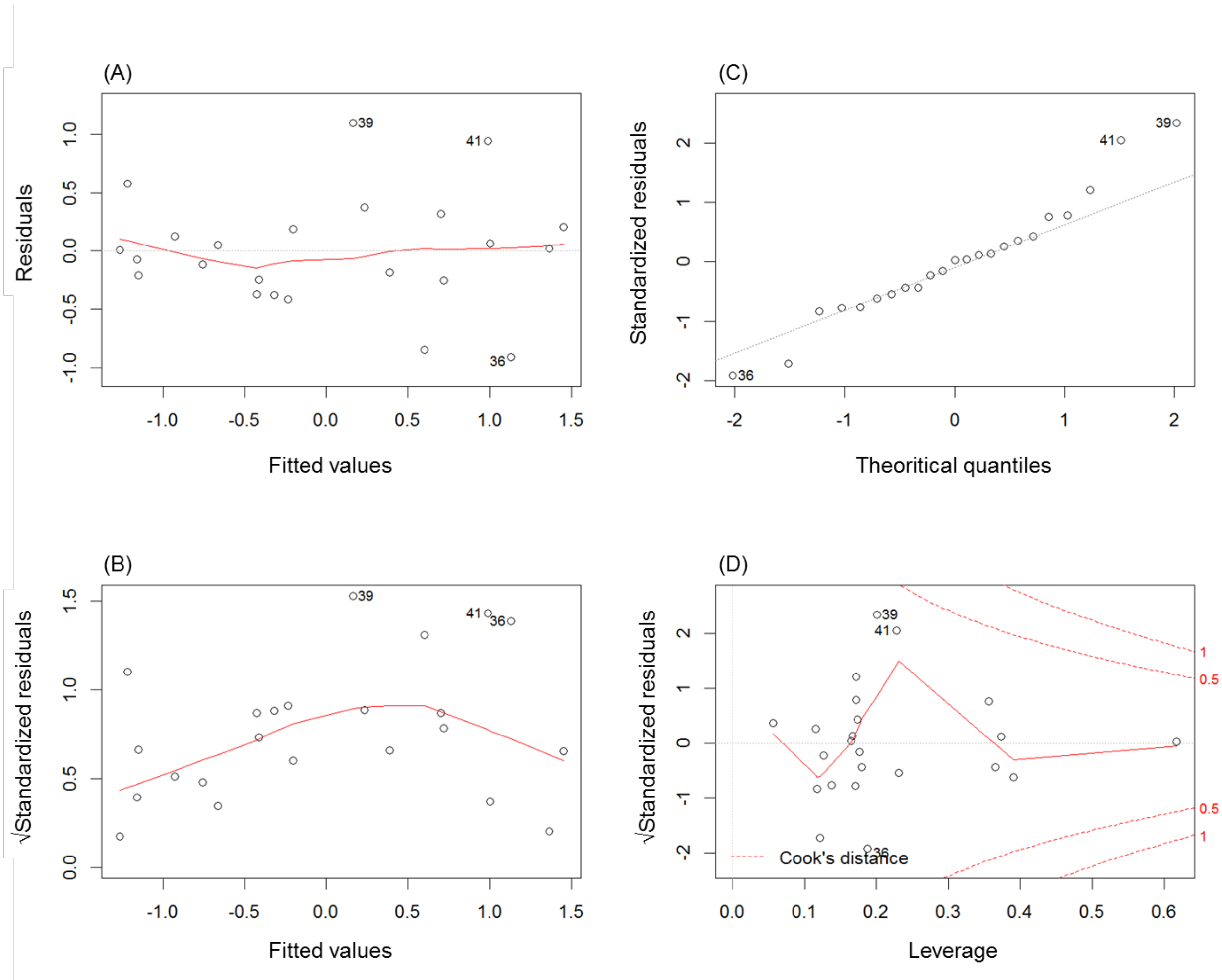

Figure 11. Diagnostic of the optimal model between PI_{t-2} and environmental descriptors. (A: residuals vs fitted values of the model, B: square root of the absolute values of the standardized residuals vs fitted values of the model, C: quantile-quantile graph of the standardized residuals and D: standardized residuals as a function of leverage graph and Cook's distances of 0.5 and 1).

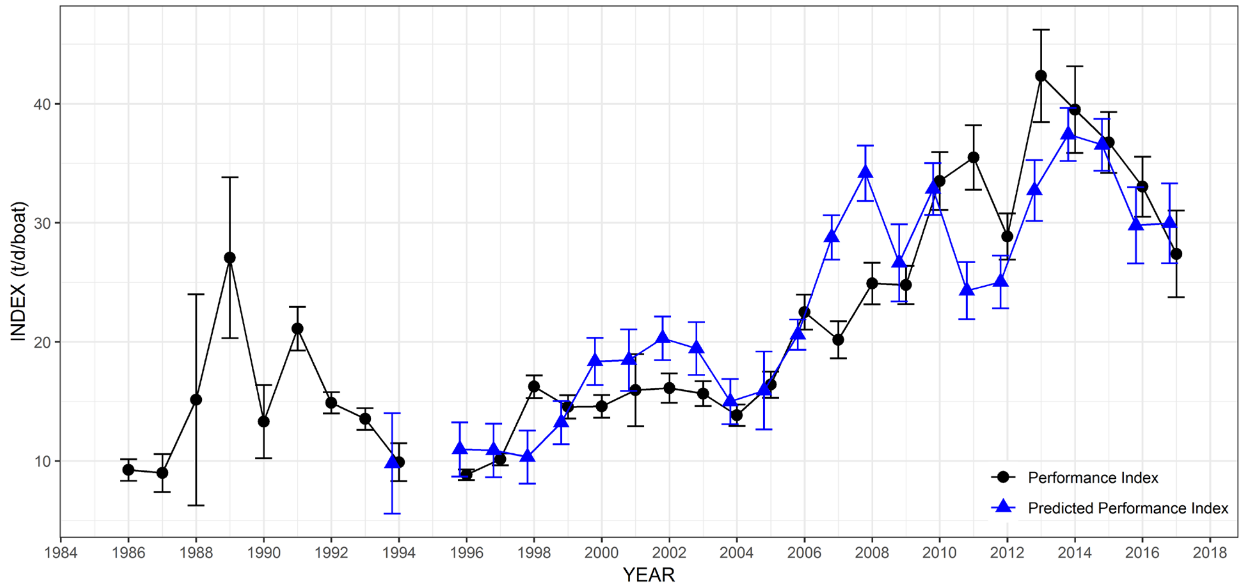

Figure 12. Comparison of the fitted values of the environmental model and the NAFO Division 4R commercial fishery performance index, ordered by year.

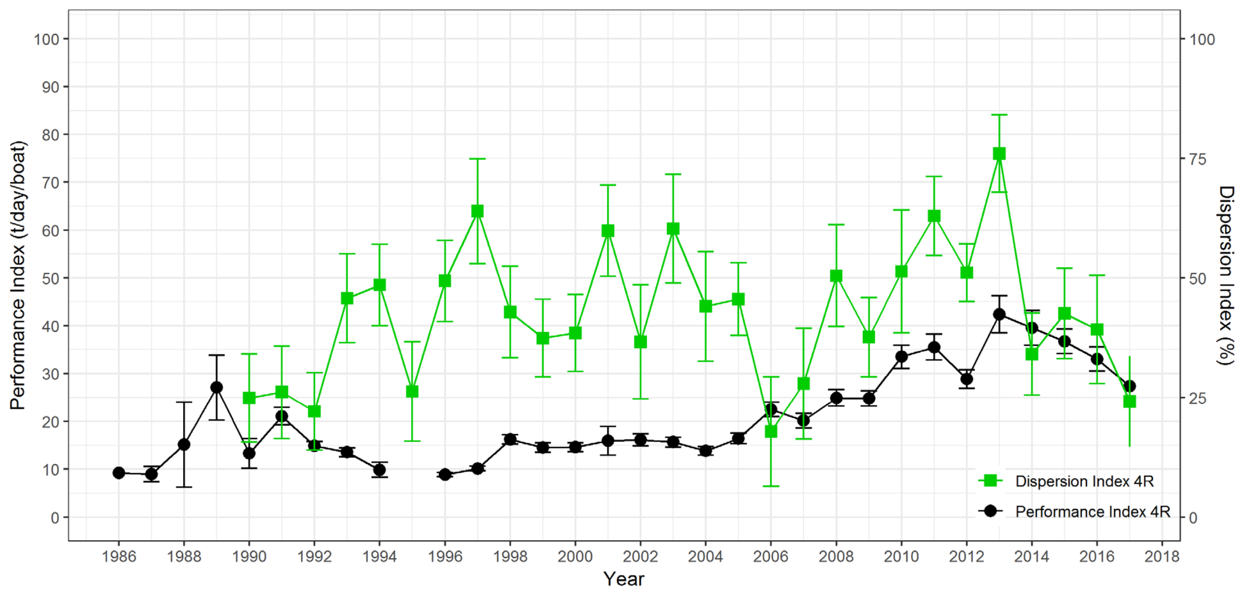

Figure 13. Comparison between the capelin commercial fishery performance index and the NAFO Division 4R dispersion index.

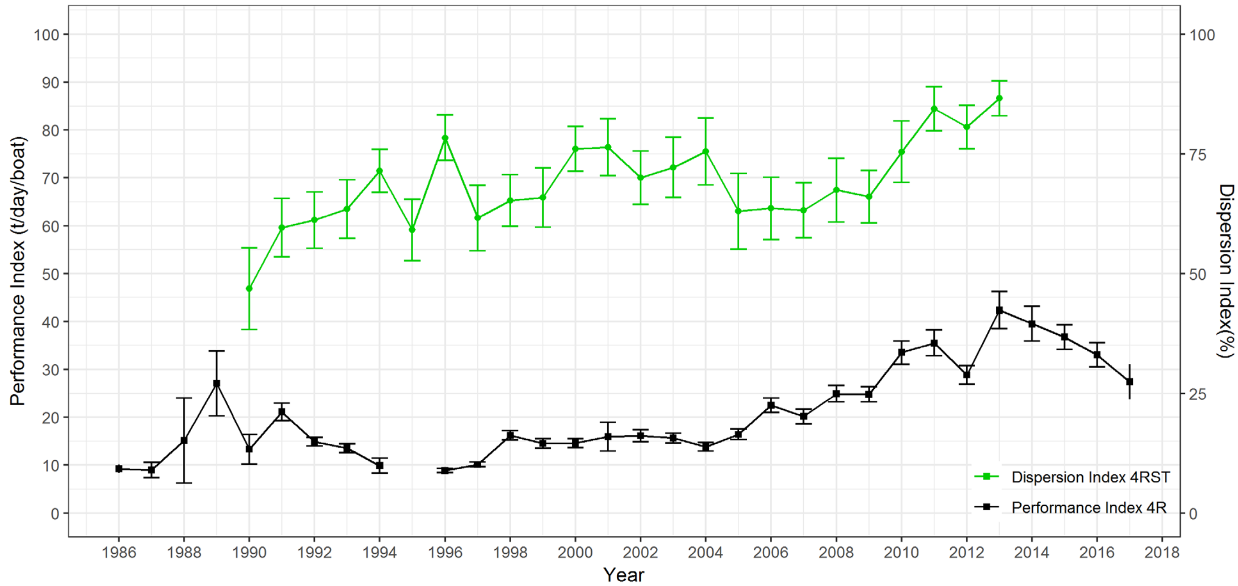

Figure 14. Comparison between the capelin commercial fishery performance index for NAFO Division 4R and the dispersion index for Divisions 4RST.

APPENDIX

APPENDIX 1: METHODOLOGY FOR CALCULATING THE ECONOMIC FACTORS THAT COULD INFLUENCE CAPELIN COMMERCIAL FISHERY PERFORMANCE

In order to test the relationship between the capelin commercial fishery performance index of NAFO Division 4R and various economic factors, data on diesel prices and landing values were compiled.

Diesel price

Fuel is the second largest expense for commercial fishers in North America (Lam et al. 2011) and is therefore an important component of the operating cost, which affects the fishery's profitability. The commercial capelin fishery in 4R is almost entirely (97%) conducted by vessels over 35 feet in length that operate on diesel. The average price of diesel was therefore used as an indicator.

Monthly average diesel prices in St John's (the only city in Newfoundland with such data) were extracted from Statistics Canada databases (Statistics Canada 2017a). In order to better represent the cost of fuel for capelin fishing, the average price for June and July was calculated for each year for which data were available (1990 to 2017).

Selling price of capelin

Another factor influencing the profitability of the fishery and possibly having an impact on fishers' behaviour is the selling price of capelin. The ZIFF data contain this information and were therefore used to calculate the mean annual price ($) per kg of capelin landed in 4R. The series thus compiled extends from 1986 to 2017.

Standardization of mean annual prices taking into account inflation

The annual mean price series for diesel and capelin both showed an upward trend due to inflation. Prices were therefore reported (deflated) on the same time base, in 2002 dollars equivalent, the year in which the Consumer Price Index (CPI) was 100 (Statistics Canada 2017b). For this, the monthly consumer price indices database (Statistics Canada 2017c) was downloaded and the Newfoundland All Items CPI (hereinafter "CPI"), which consists of a total consumer price index, was averaged per year for June and July. Subsequently, the previously calculated annual average diesel and capelin prices were converted to 2002 dollars using the following equation:

$$\text{Value}_{\$2002} = \text{Value}_{\text{year i}} * (\text{CPI}_{2002} / \text{CPI}_{\text{year i}})$$

Where $\text{Value}_{\$2002}$: Value transformed into 2002 dollars.

$\text{Year}_{\text{value i}}$: Value in dollars of year i.

$\text{CPI}_{2002:}$ June and July 2002 mean of the Newfoundland CPI.

$\text{CPI}_{\text{year i}}$: Mean of the June and July CPI in Newfoundland for year i.

The two resulting series are presented in Figures 15 and 16. It should be noted that the intra-annual variability of the capelin value is very low from 1999 onwards, which is reflected by very small standard deviations in Figure 16.

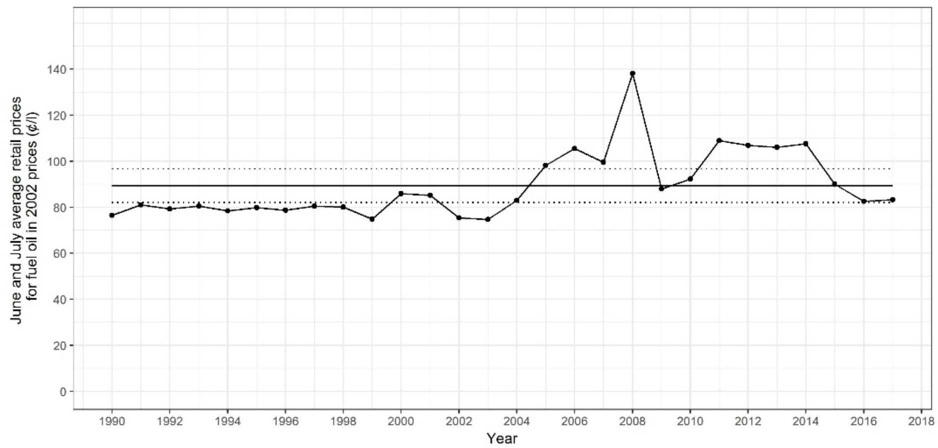

Figure 15. June and July average retail prices for fuel in St John's (Newfoundland) from 1990 to 2017. Prices are presented in 2002 values to take into account inflation. The solid horizontal line represents the average of the series and the dotted lines correspond to the average plus or minus 0.5 times the standard deviation.

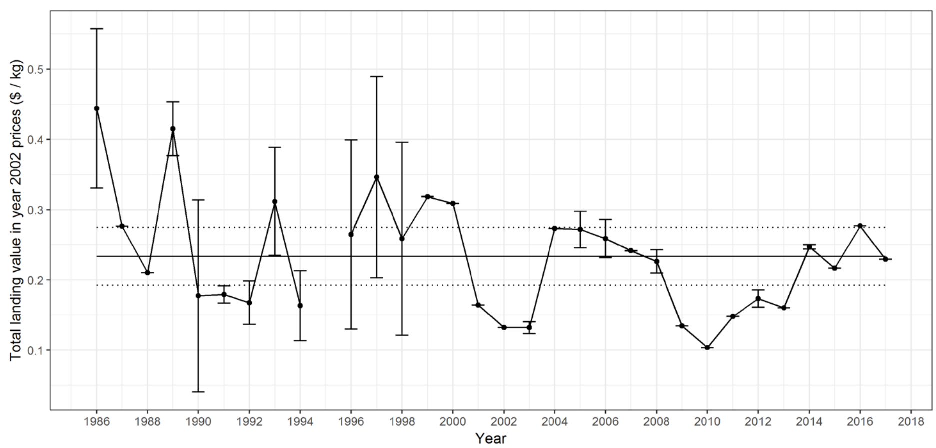

Figure 16. Mean annual price (± standard deviation) of capelin landings in 4R from 1986 to 2017. The solid horizontal line represents the mean of the series and the dotted lines correspond to the mean plus or minus 0.5 times the standard deviation.

Relationship between the capelin commercial fishery performance index in 4R and economic factors

The variation partitioning method was used since it allows for comparison of two or more complementary sets of hypotheses that can explain the variation of a response variable (Legendre and Legendre 2012). The final model between PI_{t-2} and the environmental variables was thus compared to the economic model. The latter consists of a multiple linear regression between PI_{t-2} and the variables diesel price and capelin price. The economic data series have been shifted by two years to correspond to the performance index for the same year.

The environmental model explained 72.2% of the variance of PI_{t-2}, of which 33.7% was jointly explained by the environmental and economic model. The percentage of variation explained only by the economic model was negative and therefore insignificant (Figure 17).

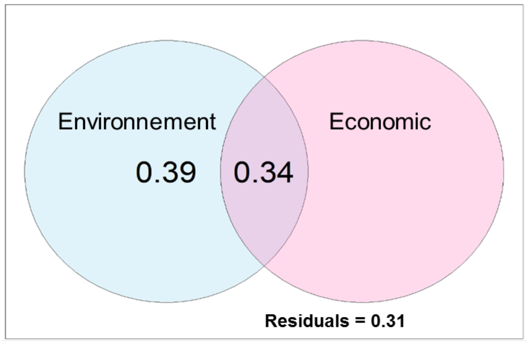

Figure 17. Venn diagram showing the variation partitioning of PI_{t-2} between the previously selected environmental variables and the economic variables lagged by two years. The reported values are the adjusted multiple determination coefficients. The proportion of variance explained solely by economic factors is 0.

Thus, the economic factors for which data were available do not explain a large proportion of the performance index variance, which provides even more support for the environmental model.