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Canadian Science Advisory Secretariat (CSAS)

Research Document 2026/062

Quebec Region

Analysis of the Overlap Between Northern Shrimp and Redfish in the Estuary and 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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

[http://www.dfo-mpo.gc.ca/csas-sccs/
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca](http://www.dfo-mpo.gc.ca/csas-sccs/DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca)



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ISSN 1919-5044

ISBN 978-1-100-00328-3 Cat. No. Fs70-5/2026-062E-PDF

Correct citation for this publication:

Poissant, D., Senay, C., and Bourdages, H. 2026. Analysis of the Overlap Between Northern Shrimp and Redfish in the Estuary and Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2026/062. iv + 46 p.

Aussi disponible en français :

Poissant, D., Senay, C., et Bourdages, H. 2026. Analyse du chevauchement de la crevette nordique et des sébastes dans l'estuaire et le golfe du Saint-Laurent. Secr. can. des avis sci. du MPO. Doc. de rech. 2026/062. iv + 46 p.

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ABSTRACT

The sharp increase in Redfish (*Sebastes mentella* and *S. fasciatus*) densities in the Estuary and Gulf of St. Lawrence, resulting from the large cohorts of 2011–2013, is cited as a partial explanation for the decline of one of their prey species, the Northern Shrimp (*Pandalus borealis*). However, documentation regarding the spatial overlap of these species and its fluctuations over time is scarce. In this paper, we use survey data from the northern Gulf from 1990 to 2025 to estimate the spatiotemporal distribution of Northern Shrimp and Redfish using models developed with the statistical tool sdmTMB. We compare fluctuations in the areas of high density for these species and use a local colocation index to track fluctuations in the degree of overlap between shrimp and Redfish. Northern Shrimp and Redfish densities fluctuated significantly during the study period, with a decline in Redfish in the early 1990s, followed by an increase in shrimp densities and a decrease in spatial overlap, before the arrival of large Redfish cohorts in 2011–2013 reversed this trend. Since 2015, spatial overlap has varied by zones: very high in Esquiman, moderate in the Anticosti and Estuary zones, and very low in Sept-Îles. Given the lack of recruitment and the high mortality rates observed among Redfish, the potential predation pressure on shrimp from Redfish is expected to continue to decline throughout the Gulf of St. Lawrence.

INTRODUCTION

The Northern Shrimp (*Pandalus borealis*) has shown a widespread decline throughout the Gulf of St. Lawrence (GSL) that began in the 2000s (DFO 2025a). The main factors cited to explain this decline are warming and oxygen depletion in the waters where shrimp occur, as well as predation by Redfish (*Sebastes mentella* and *S. fasciatus*). The trawlable biomass of Redfish has risen sharply as a result of three successive large cohorts in 2011, 2012, and 2013, reaching a peak of 4.3 million tonnes in 2019, compared to less than 100,000 tonnes prior to 2013 (Senay et al. 2023).

Northern Shrimp are preyed upon by a wide range of predators in the Estuary and Gulf of St. Lawrence (Ouellette-Plante et al. 2020), including Redfish. The diet of Redfish changes as they grow; they feed primarily on zooplankton before incorporating Northern Shrimp into their diet, along with other prey, once they reach approximately 20 cm in length (Brown-Vuillemin et al. 2022). Although predation by Redfish is often cited as one of the factors influencing the decline of the Northern Shrimp, there is very little research documenting the spatial overlap between these species.

In this research document, we assess the spatial overlap between Northern Shrimp and Redfish. We use the package sdmTMB (Anderson et al. 2024) to construct two spatiotemporal distribution models, and use the spatiotemporal predictions from both models to visualize areas of high-density overlap between Redfish and Northern Shrimp and create a collocation index for 1990 to 2025.

METHODS

DATA

The density data (kg/tow) for Northern Shrimp and Redfish come from the DFO annual ecosystem bottom trawl research survey in the Estuary and Northern Gulf of St. Lawrence (nGSL) conducted in August (Figure 1), which covers all Northern Shrimp stock assessment zones (Figure 2). The methodology of the northern Gulf of Saint-Lawrence (nGSL) survey is described in (Chamberland et al. 2025). The survey has been conducted by three vessels since 1990: the Canadian Coast Guard Ship (CCGS) *Alfred Needler* from 1990 to 2005, the CCGS *Teleost* from 2004 to 2022, and the CCGS *John Cabot* from 2021 to the present. Conversion factors to account for differences in catchability among vessels were applied (Bourdages et al. 2007; Benoît et al. 2024). A summary of standardized catches for Northern Shrimp and Redfish by stock assessment zone is presented in Tables 1, 2, 3, and 4.

Bathymetric data from the Canadian Hydrographic Service were used to incorporate depth as an environmental variable into both spatiotemporal models and the prediction grid. The depth data were transformed using a logarithmic operation before being centered and scaled. The original 50 m x 50 m resolution of the data was modified by averaging the depth values to achieve a resolution of 1 km x 1 km. Bottom temperature data for the Gulf in August were also used (St-Denis et al. 2025) as an environmental variable in both models and the prediction grid. The annual bottom temperature grids have a resolution of 2 km x 2 km; they were transformed into a 1 km x 1 km grid using inverse distance interpolation (Pebesma 2004; Gräler et al. 2016). The temperature data were mean-centered and standardized for all aggregated years.

ANALYSIS

All analyses were performed in R version 4.5.1 (R Core Team 2025). The *sdmTMB* package, version 0.7.4, was used to model the spatiotemporal distribution of shrimp and Redfish independently. *sdmTMB* fits spatiotemporal mixed-models, where one or more fixed effects (i.e., one or more environmental variables) are combined with one or more random effects to model the spatiotemporal variance not explained by the fixed effects. Further details on the *sdmTMB* methodology are available in Anderson et al. (2024).

Model specification

The mesh was generated using the *make_mesh* function from the *sdmTMB* library. A cutoff of 10 km was used because this distance is small enough to maximize prediction accuracy while maintaining a reasonable computation time. A barrier corresponding to the coastlines was included in the mesh to prevent the spatial influence of observations across terrestrial areas. The *sdmTMB* models for Northern Shrimp and Redfish density include a spatial field and random-walk spatiotemporal fields. Various distribution families were evaluated to model the dependent variable (density, in kg per tow), and the Tweedie distribution was selected for both species after examining the residuals. The effect of environmental variables was modeled using a smoothing function (*s*), with the value of *k* (number of basis dimension) set to 10, the default value. Environmental variables were extracted from the prediction grid to fit the models. This ensured that the scaling remained consistent between the data used for model fitting and the data used for spatial prediction. The year of observation was also included in the fixed effects. An offset corresponding to the trawled area for each tow in km² was included in the models.

Cross-validation

To determine whether bottom temperature improves the model's predictions, the *sdmTMB_cv* function (see Anderson et al. 2026) was used to perform cross-validation between a model containing only depth, a model containing depth and temperature, and a model with a depth and bottom temperature interaction. The cross-validation was performed on 20 data blocks; the same data blocks were used for each model. The results of the cross-validation are presented in APPENDIX A : CROSS-VALIDATION RESULTS. For Northern Shrimp and Redfish, the cross-validation suggests that including a smoothed interaction term for temperature and depth improves the predictions.

Model diagnosis

The *sanity* function in *sdmTMB* was used to verify model convergence and the standard errors of the model parameters. The residuals were also examined using the DHARMA library (Hartig 2016) to verify the theoretical and predicted distribution of the residuals, zero inflation, and spatial autocorrelation. The simulated residuals are of the 'mle-mvn' type (Maximum likelihood estimate-multivariate normal). Diagnostic figures for the spatiotemporal models of shrimp and Redfish are available in APPENDIX B : DIAGNOSIS OF SPATIOTEMPORAL MODELS.

Predictions and spatial overlap index

Predictions were made using a grid containing depth and temperature data for each year between 1990 and 2025. Only grid cells with depths of 35 m or greater were included, which corresponds to the minimum depth sampled during the survey. Predictions were made using an offset corresponding to the area swept by a standard 15-minute tow on the NGCC *John Cabot*, i.e., 0.0227 km².

To map the spatiotemporal overlap of shrimp and Redfish, the distribution of predicted densities was divided into three categories for each species separately before being cross-tabulated to create a matrix of nine categories. The predicted catch categories for Redfish are 0–10 kg, 10–390 kg, and 390 kg and over. The categories for shrimp are 0–1 kg, 1–24 kg, and 24 kg and above. These categories represent the tertiles of the catches observed in the survey during the years of highest abundance (Northern Shrimp: 2004–2012, Redfish: 2018–2022). The density category matrix thus allows for the spatial representation of areas where low, medium, and high densities of each shrimp and Redfish species overlapped, as well as for measuring the temporal change in the area of low, medium, and high densities for shrimp and Redfish species independently.

The local collocation index (Equation 1) was calculated independently for each year. The local collocation index assesses the co-occurrence of two groups of organisms using their respective biomass proportions to determine their correlation (Carroll et al. 2019). Since the local collocation index uses the annual proportion of species biomass, the index represents only the degree of spatial overlap for a single year and is insensitive to interannual fluctuations in absolute biomass.

$$I_j = \frac{\sum_i^n (p_{shrimp\ ji} * p_{redfish\ ji})}{\sqrt{\sum_i^n p_{shrimp\ ji}^2 * \sum_i^n p_{redfish\ ji}^2}} \quad (1)$$

Where I_j is the local collocation index for year j , $p_{shrimp\ ji}$ is the proportion of the annual Northern Shrimp biomass for year j in cell i , and $p_{redfish\ ji}$ is the proportion of the annual Redfish biomass for year j in cell i .

RESULTS

PREDICTIONS

Northern Shrimp

The spatio-temporal shrimp model indicates that the highest shrimp catches occur at depths between approximately 150 and 300 m and at temperatures between 2.5 °C and 7.5 °C (Figure 3). Figures 4, 5, 6, and 7 show the annual spatial predictions for Northern Shrimp. The highest densities were found north of Anticosti Island in 2007 (Figure 5) and in the Estuary in 2021 (Figure 7). Shrimp density shows strong fluctuations in all areas; it has increased since 1990, peaking in the 2000s in Anticosti, Esquiman, and Sept-Îles, and in 2021 in the Estuary, before falling back to values similar to those observed in the early 1990s in all areas, with the exception of the Estuary (Figure 8). However, examination of the residuals reveals that 40% of the highest predicted values underestimate the observed catches and that the model suffers from underdispersion (see APPENDIX B : DIAGNOSIS OF SPATIOTEMPORAL MODELS). Furthermore, the maximum catches predicted by the model (approximately 13.5 tons) far exceed the maximum catch values actually observed in the survey (maximum value of 940 kg [result not shown in the figures]).

Redfish

The spatiotemporal model for Redfish indicates that the highest Redfish catches occur at depths of approximately 200 m and water temperatures of approximately 6 °C (Figure 9). Figures 10, 11, 12, and 13 show the annual spatial predictions for Redfish. Predicted Redfish catch values

fluctuated significantly during the analysis period, dropping in 1992 before rebounding starting in 2013. In recent years, the largest Redfish aggregations have been located in Esquiman as well as in the Sept-Îles zone, on the slope of the Magdalen Shelf (Figure 13).

Redfish density declined sharply in the early 1990s in Anticosti, Esquiman, and Sept-Îles and remained very low until 2011, when biomass increased sharply, peaking in 2019 before declining slightly. In the Estuary, the density of Redfish remained much lower than in the other zones (Figure 8). Examination of the residuals does not reveal any major issues for the spatiotemporal model of Redfish (see APPENDIX B: DIAGNOSIS OF SPATIOTEMPORAL MODELS).

OVERLAP OF NORTHERN SHRIMP AND REDFISH

Overlap maps

Figures 14, 15, 16, and 17 show the spatiotemporal overlap between Northern Shrimp and Redfish. In the Estuary zone, shrimp densities showed significant fluctuations in spatial coverage. The area of high Redfish densities remained very small in the Estuary; a small area of high shrimp and Redfish density was observed from 2015 to 2017 (Figure 18). The Estuary zone must, however, be analyzed with caution, as this is the zone where the quality of spatiotemporal model predictions appears to be the lowest (see APPENDIX B : DIAGNOSIS OF SPATIOTEMPORAL MODELS), that certain strata were added there only starting in 2008, and that the spatial coverage of the survey fluctuated significantly over the course of the survey (Table 1).

Regarding the Sept-Îles zone, high densities of shrimp and Redfish overlapped primarily from 2013 to 2019 (Figure 19). The years 1994 through 2013 were characterized by a large area of high Northern Shrimp densities free of Redfish in the Sept-Îles zone. The vast majority of the spatial coverage of high Redfish densities was concentrated in areas of low Northern Shrimp density.

In Anticosti, high densities of shrimp and Redfish overlapped from 1990 to 1993, and then more significantly starting in 2014 (Figure 20). The years 1993 through 2014 were characterized by high densities of shrimp and very low densities of Redfish in Anticosti. Most of the area covered by high Redfish densities starting in 2014 had low or moderate Northern Shrimp densities; high densities of shrimp and Redfish overlapped over a relatively small area.

In the Esquiman zone, the early 1990s featured a small area of overlap between high shrimp and Redfish densities (Figure 21). The period from 1995 to 2013 was characterized by high shrimp densities and low Redfish densities. Since 2015, the area of high Redfish density has increased significantly; this increase was greater in areas of medium shrimp density, and to a similar extent in areas of low and high shrimp density.

Local collocation index

The local collocation index indicates that the spatial overlap between Northern Shrimp and Redfish fluctuated significantly during the study period. In the Estuary, following a relatively high level of overlap between 1990 and 2010, the overlap index declined gradually, reaching a low point in 2020. Since then, the overlap index has been gradually rising back toward its historical average. In the Sept-Îles zone, overlap reached a historical peak in 2014–2015, before dropping sharply to the lowest value in the series in 2020, even though the average Redfish density was among the highest values observed. The overlap index has remained very low there since then.

In the Anticosti zone, overlap reached two peaks, one between 1990–1992 and a second in 2013–2015, before dropping sharply in 2017 and recovering to an intermediate level since then (Figure 22). In the Esquiman zone, the local collocation index indicates relatively high overlap in 1990–1992, followed by a sharp decrease before gradually rising through 2025; the index in 2025 is among the highest values of the study period. The Esquiman zone is the only one where high co-occurrence index values coincide temporally with high Redfish density values.

DISCUSSION AND CONCLUSION

The densities and spatial overlap of Northern Shrimp and Redfish fluctuated significantly during the study period. At the Estuary and Gulf of St. Lawrence scale, the early 1990s were characterized by high Redfish densities, low Northern Shrimp densities, and significant spatial overlap. The decline of Redfish in 1993 was followed by a widespread increase in shrimp densities and a significant decrease in spatial overlap in the Estuary and Gulf of St. Lawrence. The arrival of the large Redfish cohorts of 2011–2013 resulted in increased spatial overlap between the two species, a very marked increase in Redfish density, and, implicitly, a likely increase in predation potential.

Since then, trends in spatial overlap have fluctuated by zones. In the Estuary, despite increasing spatial overlap as indicated by the local collocation index, the very low estimated Redfish densities likely limit the impact that Redfish predation could have on Northern Shrimp stocks. After peaking in 2014–2015 in Sept-Îles, the two species now occupy distinct areas. In Anticosti, after a sharp decline in 2017, spatial overlap is trending upward. In Esquiman, spatial overlap remains among the highest values in the historical series.

The potential predation pressure exerted by Redfish on Northern Shrimp is an underlying theme of the analysis presented in this document. However, several limitations prevent the establishment of a direct link between spatial overlap and actual predation. The lack of observations during months of the year other than August limits our understanding of seasonal variations in the overlap between these species. Furthermore, the estimation of predation pressure is limited by the estimation of variations in individual shrimp consumption by Redfish, which can vary depending on the density of both shrimp and Redfish (Boussens-Dumon et al. 2025), as well as on the Redfish's size (Brown-Vuillemin et al. 2022). Further efforts will be needed to integrate these variables into a model that would allow for the precise tracking of Redfish predation pressure on Northern Shrimp (see Lindmark et al. (2025) for an example). Moreover, the spatiotemporal model for Northern Shrimp still exhibits visible issues in residual diagnostics, despite considering various different model formulations that did not produce a better fit (not presented in this document). Further efforts would also be needed to improve the accuracy of the shrimp model's predictions. Furthermore, Northern Shrimp are also preyed upon by several predators, notably Atlantic Cod (*Gadus morhua*) and Greenland Halibut (*Reinhardtius hippoglossoides*), whose populations experienced significant fluctuations during the study period. Future modeling work could incorporate these predators to better understand shrimp dynamics. In any case, given the lack of recruitment, limited growth, and high mortality observed for Redfish in the Estuary and Gulf of St. Lawrence (DFO 2025b), it is likely that the potential for predation by Redfish will continue to decline across the Gulf in the near future.

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TABLES

Table 1: Summary of raw catches (kg, CCGS John Cabot standard tow) of Northern Shrimp and Redfish by year in the Estuary Northern Shrimp stock assessment zone.

Year	Number of successful random tow	Northern Shrimp		Redfish	
		Mean	Maximum	Mean	Maximum
1990	12	7.1	24.1	3.1	8.7
1991	11	5.8	20.8	2.3	8.5
1992	11	4.6	35.6	4.4	13.4
1993	12	5.5	34.4	1.0	7.3
1994	8	9.1	52.6	1.5	3.2
1995	18	1.4	9.4	0.5	2.5
1996	17	13.8	80.7	0.4	1.6
1997	16	3.0	26.3	0.6	5.8
1998	14	2.5	12.9	1.6	10.2
1999	21	12.9	98.5	1.0	15.7
2000	17	8.2	30.0	0.6	1.8
2001	19	4.7	27.0	2.8	42.8
2002	12	2.4	14.8	8.7	91.6
2003	11	6.4	49.5	0.8	3.3
2004	9	14.9	78.1	6.3	39.5
2005	24	8.5	42.8	1.9	24.7
2006	12	3.6	11.5	2.8	26.0
2007	12	2.7	13.9	0.4	2.3
2008	21	28.1	133.6	0.4	1.8
2009	23	26.3	104.1	0.5	6.9
2010	24	22.0	194.8	1.1	12.2
2011	21	27.1	189.8	8.2	120.0
2012	19	23.4	97.1	0.3	1.4
2013	20	22.2	113.6	3.3	13.5
2014	15	28.6	102.6	6.2	47.5
2015	14	12.9	45.8	17.7	97.1
2016	15	33.2	192.1	66.7	512.9
2017	14	7.6	41.8	80.1	273.7
2018	17	21.8	259.0	43.2	238.9
2019	10	30.9	163.6	68.9	430.4
2020	10	6.5	42.3	9.4	35.8
2021	26	58.0	383.5	3.0	16.7
2022	32	73.0	742.0	2.1	18.6
2023	0	-	-	-	-
2024	15	39.2	248.4	0.2	1.1
2025	16	25.3	255.0	0.6	5.2

Table 2: Summary of raw catches (kg, CCGS John Cabot standard tow) of Northern Shrimp and Redfish by year in the Sept-Îles Northern Shrimp stock assessment zone.

Year	Number of successful random tow	Northern Shrimp		Redfish	
		Mean	Maximum	Mean	Maximum
1990	86	12.8	167.6	209.5	4324.7
1991	96	20.2	279.4	77.8	1301.3
1992	86	7.1	89.9	47.3	330.3
1993	69	10.2	66.2	61.8	2979.8
1994	71	14.8	115.1	10.6	81.7
1995	73	19.7	117.2	19.2	239.0
1996	92	26.1	186.5	9.3	108.2
1997	74	29.6	169.3	11.7	84.8
1998	69	29.0	161.5	41.6	2247.4
1999	84	27.1	146.5	11.1	123.3
2000	72	41.7	160.1	14.2	174.4
2001	78	36.1	271.4	12.2	147.2
2002	73	40.8	341.1	7.9	151.8
2003	62	91.9	860.2	89.1	4355.8
2004	52	56.0	254.7	16.0	236.2
2005	123	40.8	228.2	15.7	156.4
2006	66	38.4	251.7	17.0	231.8
2007	72	48.9	420.4	20.3	558.3
2008	66	40.5	242.6	48.8	1808.7
2009	68	27.3	255.4	14.3	440.3
2010	53	35.0	168.5	28.4	927.7
2011	59	22.6	91.3	17.3	139.3
2012	64	29.8	319.2	19.9	127.2
2013	62	23.0	277.0	59.1	2009.5
2014	67	29.6	334.9	74.8	688.7
2015	72	25.1	167.5	133.0	2322.5
2016	62	19.9	272.3	335.9	2416.0
2017	69	8.4	102.2	449.9	4729.0
2018	51	6.6	65.2	452.1	2518.4
2019	51	8.4	124.5	663.3	4892.9
2020	56	13.1	119.9	814.1	21329.7
2021	62	7.9	81.8	556.8	3908.3
2022	121	1.8	52.3	362.2	4889.4
2023	43	2.4	33.6	687.0	11062.2
2024	61	4.4	57.6	397.6	3163.2
2025	47	6.3	74.3	495.6	11205.0

Table 3: Summary of raw catches (kg, CCGS John Cabot standard tow) of Northern Shrimp and Redfish by year in the Anticosti Northern Shrimp stock assessment zone.

Year	Number of successful random tow	Northern Shrimp		Redfish	
		Mean	Maximum	Mean	Maximum
1990	37	17.8	68.0	171.5	1013.8
1991	49	13.9	43.5	205.2	2359.7
1992	51	13.3	118.8	261.2	7177.0
1993	44	10.0	87.1	54.2	823.2
1994	35	7.5	39.1	25.5	420.0
1995	35	17.2	100.6	10.4	73.0
1996	39	33.5	185.5	14.1	119.6
1997	33	26.6	125.1	41.9	1159.0
1998	50	21.3	61.5	9.3	115.1
1999	47	21.6	86.2	7.5	51.4
2000	49	28.8	133.5	8.9	97.6
2001	9	10.3	20.9	13.3	61.5
2002	25	32.5	126.6	12.7	122.7
2003	25	47.5	263.6	13.1	141.9
2004	18	41.6	307.0	3.3	19.4
2005	65	41.5	234.4	14.3	143.6
2006	41	27.7	203.9	16.2	181.9
2007	39	42.4	409.3	19.4	155.6
2008	40	15.9	66.6	34.5	821.2
2009	33	30.9	110.3	8.8	95.0
2010	31	26.2	123.6	15.6	147.9
2011	29	10.7	71.7	13.9	105.3
2012	30	13.3	60.9	18.2	219.0
2013	24	19.5	121.2	12.3	92.7
2014	31	21.1	157.6	59.9	447.0
2015	38	24.6	256.9	135.2	795.2
2016	35	12.0	88.8	509.3	3236.7
2017	35	16.8	131.1	687.8	4932.0
2018	39	9.2	82.4	771.4	4453.8
2019	23	14.2	86.0	1123.4	4169.5
2020	21	13.5	70.9	450.6	3450.2
2021	34	10.4	155.8	750.1	5583.1
2022	86	4.9	60.2	673.3	4995.9
2023	25	3.8	25.0	546.8	2996.3
2024	31	7.9	33.7	468.2	3552.9
2025	35	14.3	92.9	280.2	2714.2

Table 4: Summary of raw catches (kg, CCGS John Cabot standard tow) of Northern Shrimp and Redfish by year in the Esquiman Northern Shrimp stock assessment zone.

Year	Number of successful random tow	Northern Shrimp		Redfish	
		Mean	Maximum	Mean	Maximum
1990	49	13.4	105.1	264.4	2203.2
1991	86	6.9	67.7	161.5	2724.9
1992	86	4.7	59.2	85.6	616.0
1993	79	5.4	42.3	29.3	501.6
1994	55	5.3	50.7	120.0	5198.1
1995	51	10.9	111.9	26.1	214.4
1996	63	11.3	125.3	26.7	356.9
1997	56	25.9	390.7	34.4	443.2
1998	64	14.7	121.7	20.2	249.4
1999	63	22.0	336.7	21.5	417.2
2000	64	19.4	218.6	27.4	210.6
2001	70	17.4	129.6	30.2	1102.7
2002	54	6.4	105.7	43.4	1060.7
2003	59	33.5	241.3	27.4	257.8
2004	49	23.6	245.2	12.5	228.1
2005	131	16.2	257.8	41.2	1031.5
2006	65	23.0	284.3	46.9	991.5
2007	55	15.0	109.4	54.8	988.4
2008	69	15.5	257.1	24.3	229.0
2009	50	21.0	125.6	9.6	70.2
2010	34	26.3	195.9	8.6	38.5
2011	52	23.9	161.5	11.7	93.4
2012	66	17.4	402.8	11.9	131.9
2013	41	23.2	170.8	45.1	836.3
2014	66	17.2	187.3	53.0	667.9
2015	60	13.0	171.5	72.5	862.1
2016	49	14.4	208.9	263.6	2610.6
2017	49	8.8	63.6	532.0	4847.0
2018	55	9.8	160.9	765.7	6653.0
2019	38	19.2	158.8	1271.2	11416.7
2020	54	6.7	94.4	459.7	5907.4
2021	42	10.6	68.8	688.3	4811.9
2022	109	8.5	111.7	710.1	11163.2
2023	38	7.4	65.2	582.0	3998.2
2024	53	4.0	39.4	375.7	2221.3
2025	54	5.6	57.0	364.0	2040.4

FIGURES

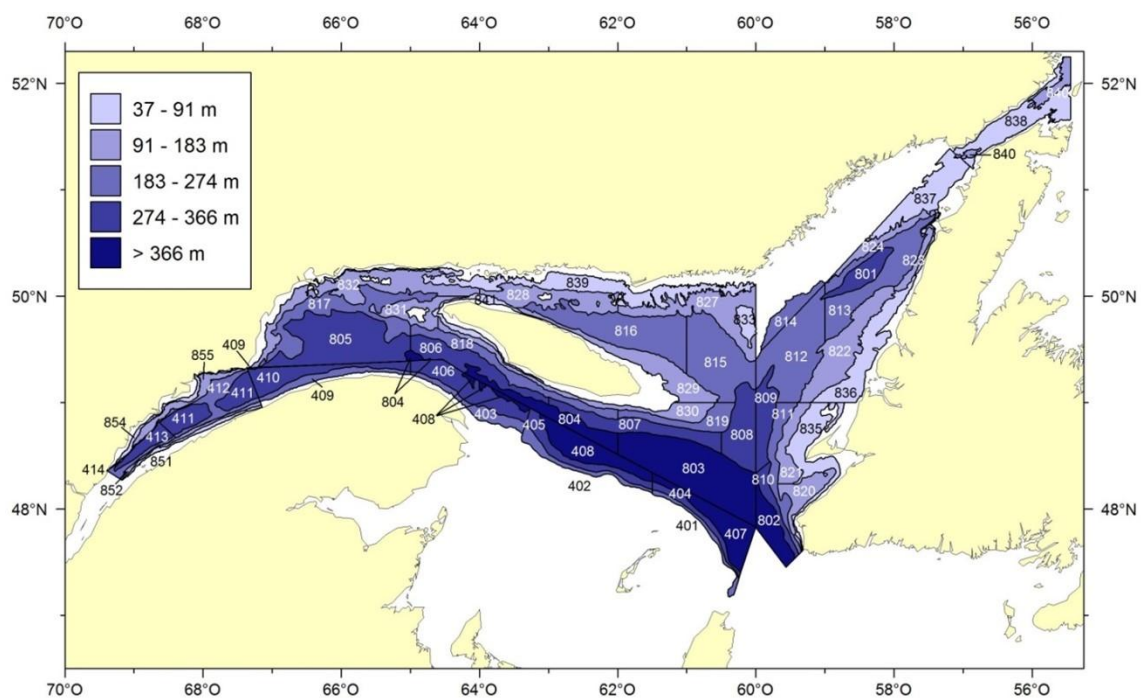


Figure 1: Stratification scheme used for the survey of groundfish and shrimp in the Estuary and Northern Gulf of St. Lawrence.

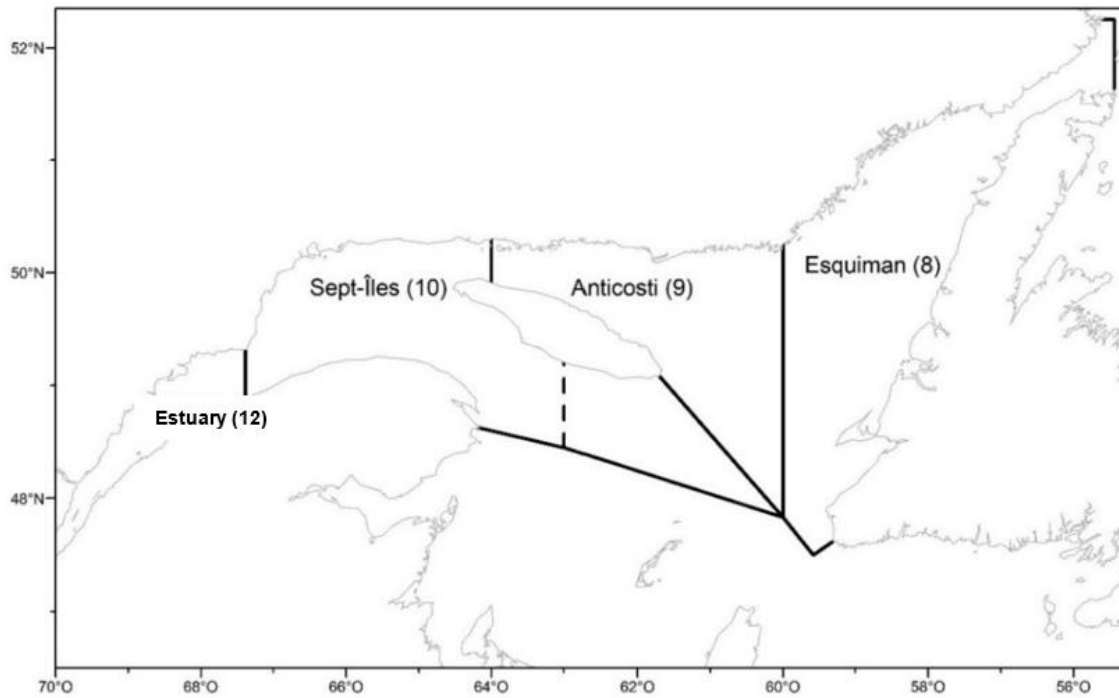


Figure 2: Boundaries of the Northern Shrimp stock assessment zones (solid line). The dashed line south of Anticosti Island corresponds to the former boundary separating the Sept-Îles and Anticosti zones. Adapted from MPO (2023).

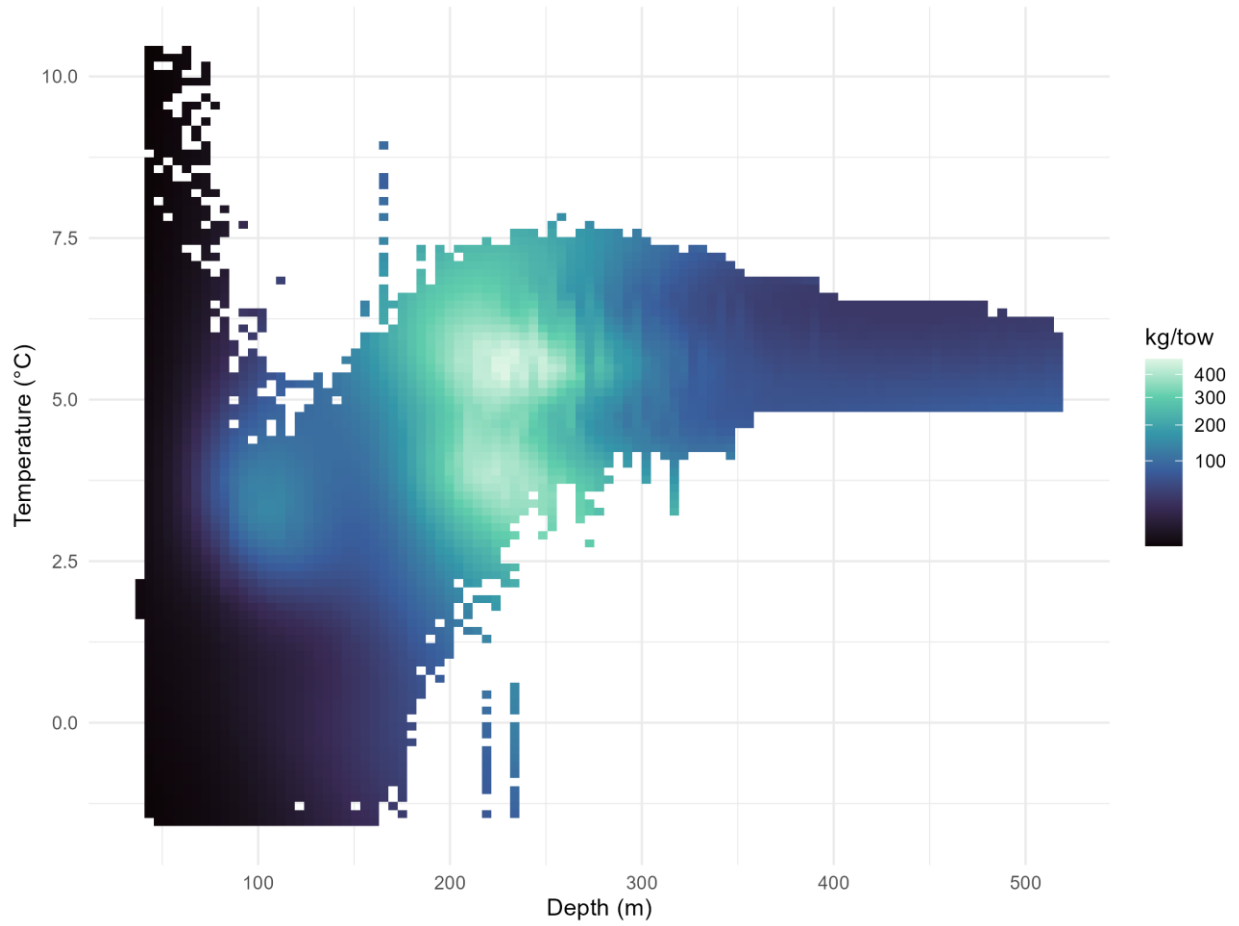


Figure 3: Effect of depth and temperature on shrimp density according to the model. Only the existing combinations of depth and temperature observed in the prediction grid were included.

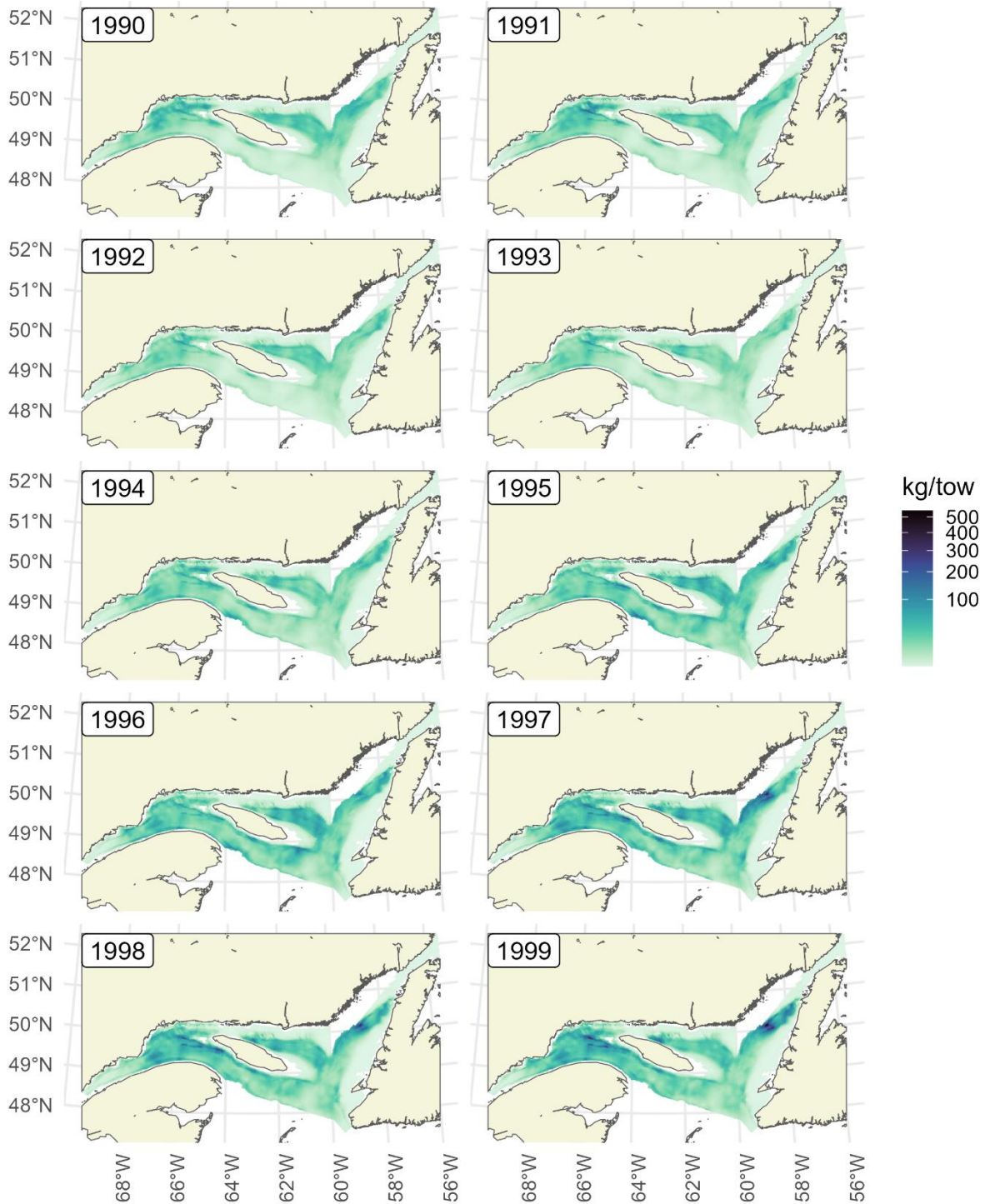


Figure 4: Predictions of Northern Shrimp density from the spatiotemporal model for the Gulf of St. Lawrence in August, between 1990 and 1999.

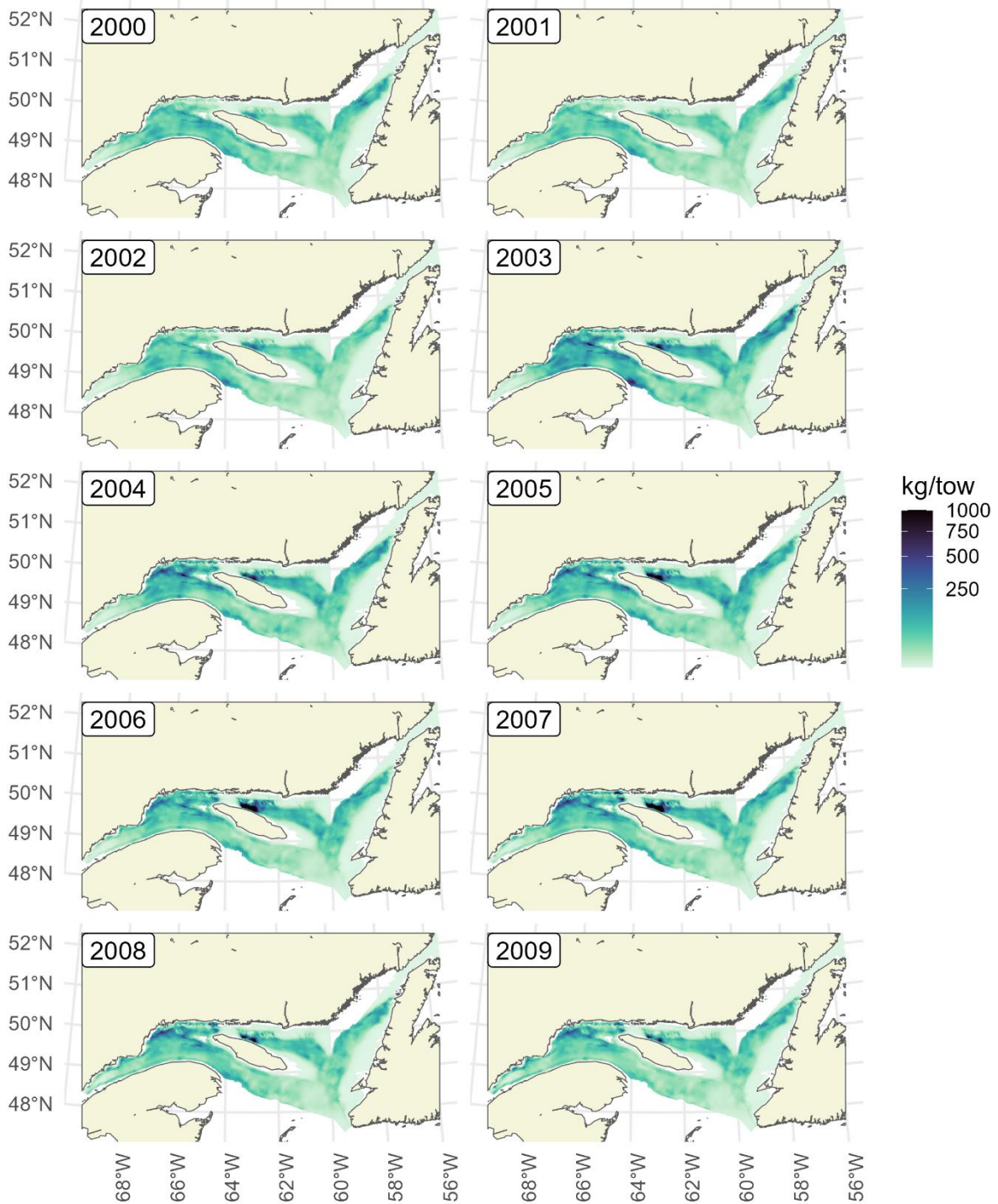


Figure 5: Predictions of Northern Shrimp density from the spatiotemporal model for the Gulf of St. Lawrence in August, between 2000 and 2009. Values greater than 1,000 kg have been capped at 1,000 kg to improve the visibility of values across the study area.

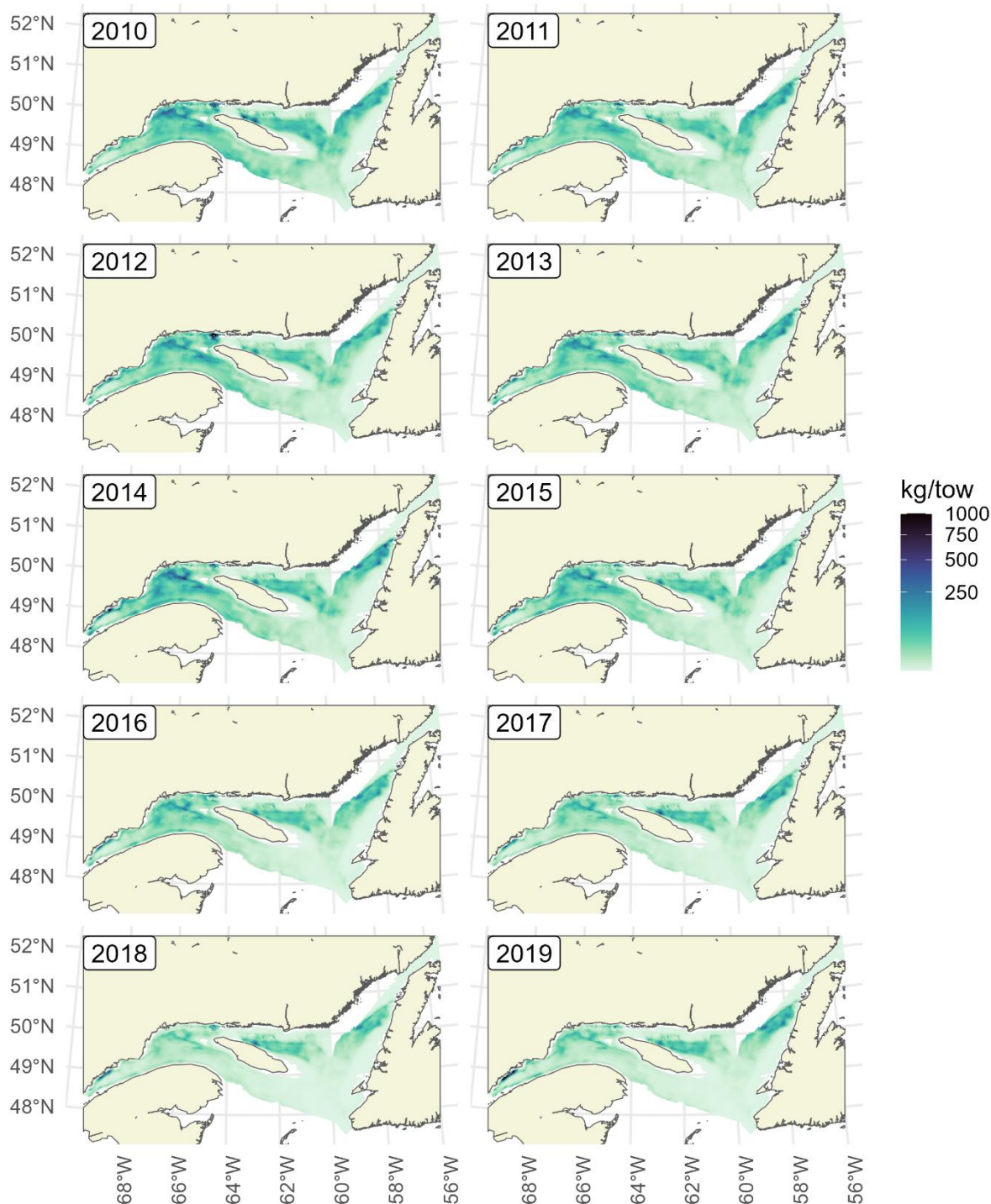


Figure 6: Predictions of Northern Shrimp density from the spatiotemporal model for the Gulf of St. Lawrence in August, between 2010 and 2019. Values greater than 1,000 kg have been capped at 1,000 kg to improve the visibility of values across the study area.

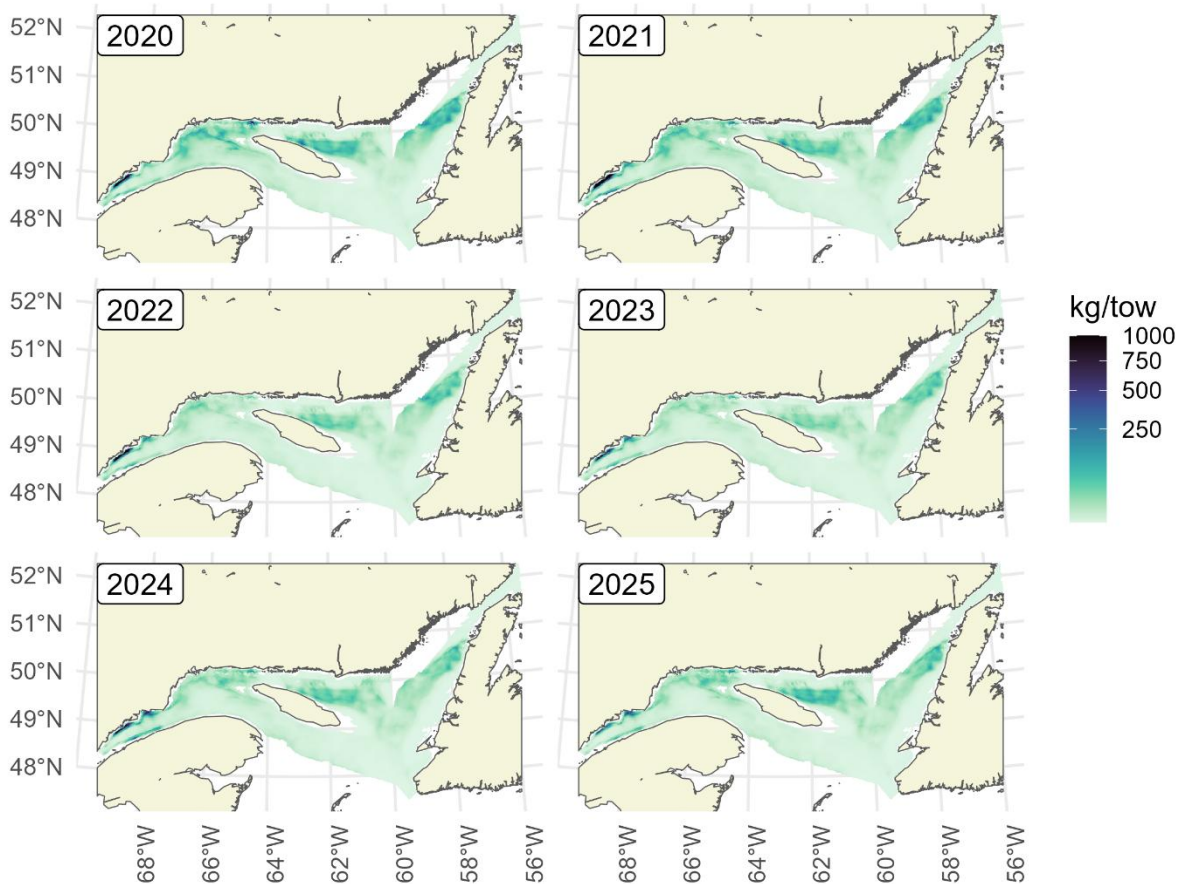


Figure 7: Predictions of Northern Shrimp density from the spatiotemporal model for the Gulf of St. Lawrence in August, between 2020 and 2025. Values greater than 1,000 kg have been capped at 1,000 kg to improve the visibility of values across the study area.

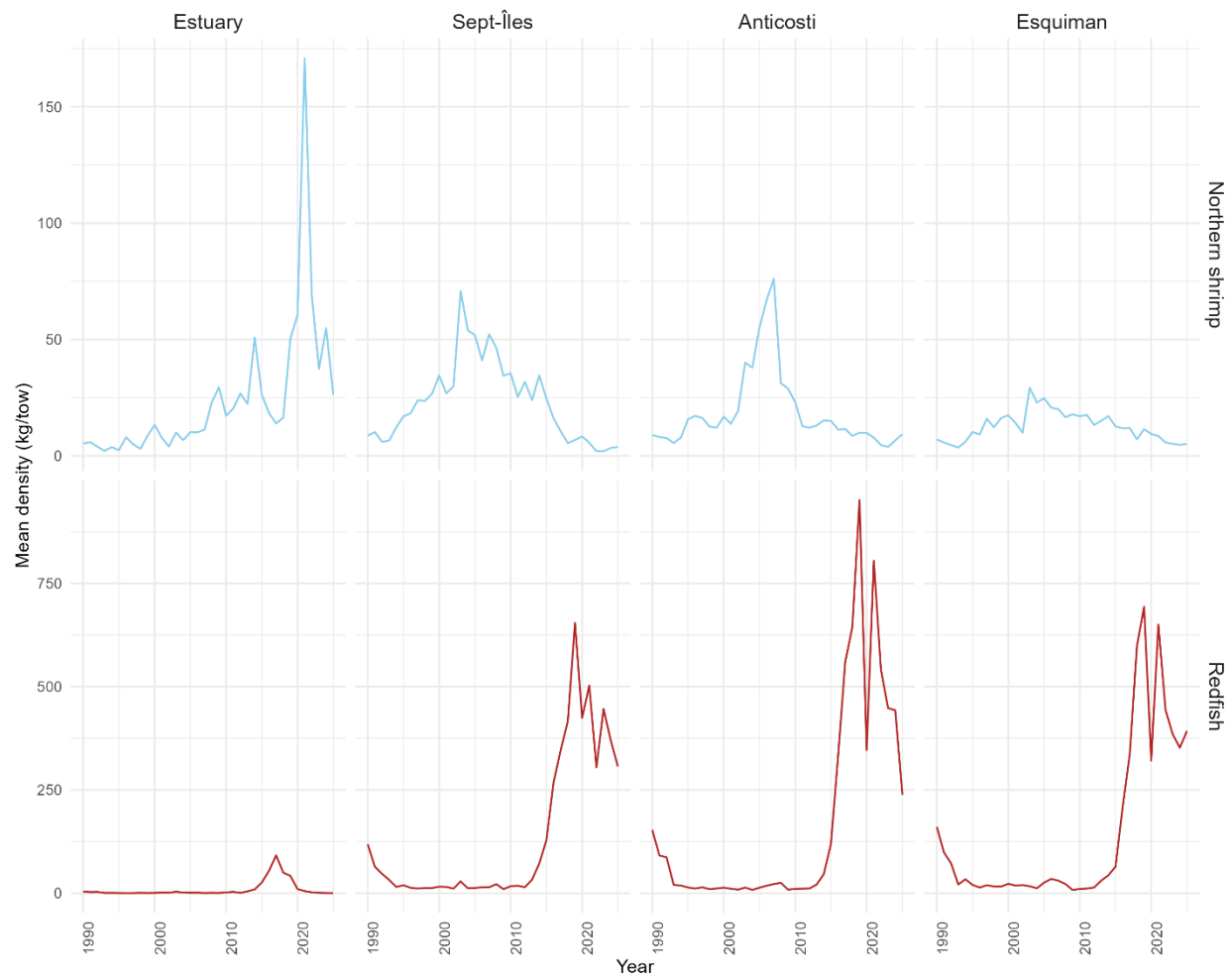


Figure 8: Average density of Northern Shrimp and Redfish in the Estuary and Gulf of St. Lawrence from 1990 to 2025, by Northern Shrimp stock assessment zone.

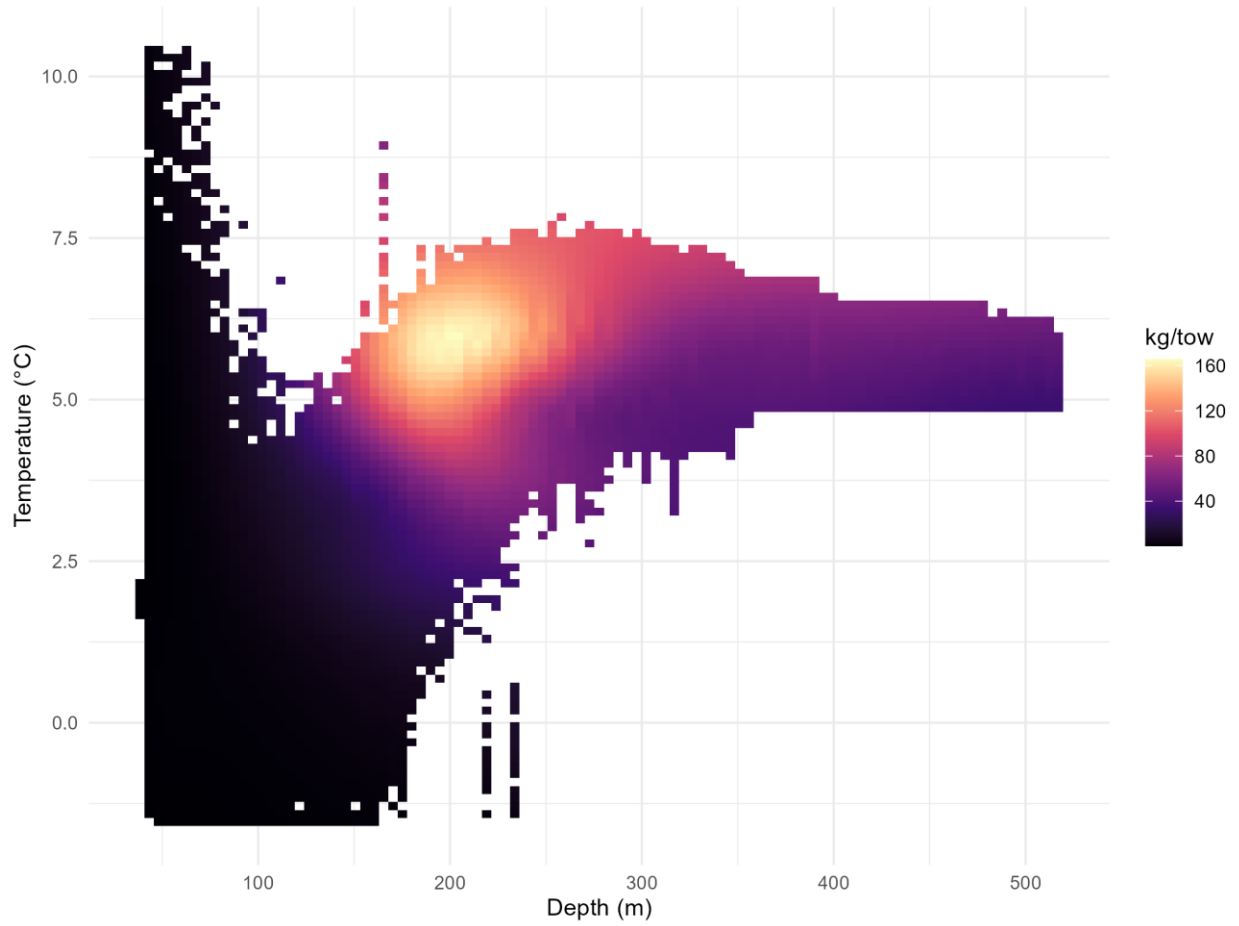


Figure 9: Effect of depth and temperature on the density of Redfish according to the model. Only the existing combinations of depth and temperature observed in the prediction grid were included.

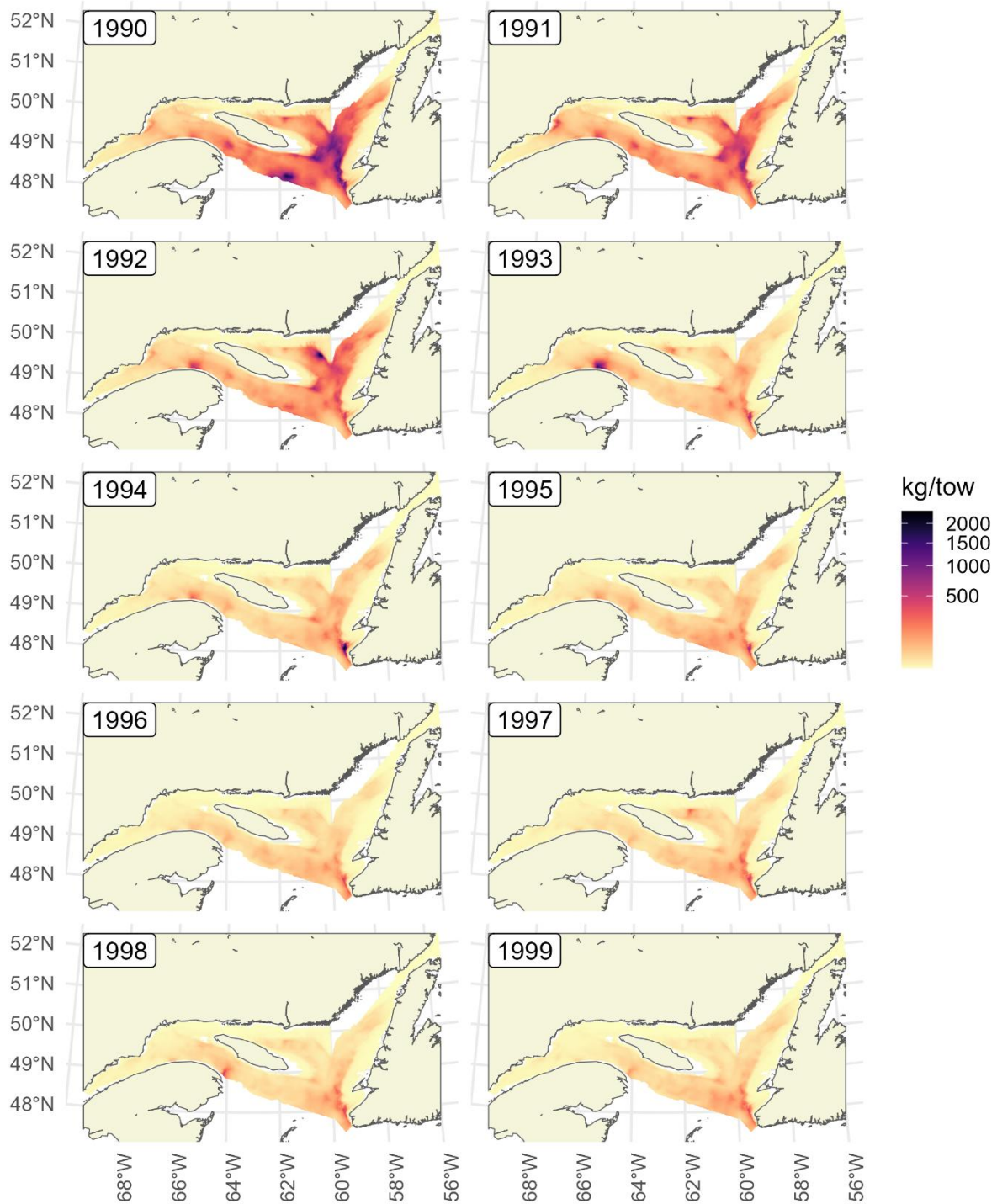


Figure 10: Predictions of Redfish density from the spatiotemporal model for the Estuary and Gulf of St. Lawrence in August, between 1990 and 1999.

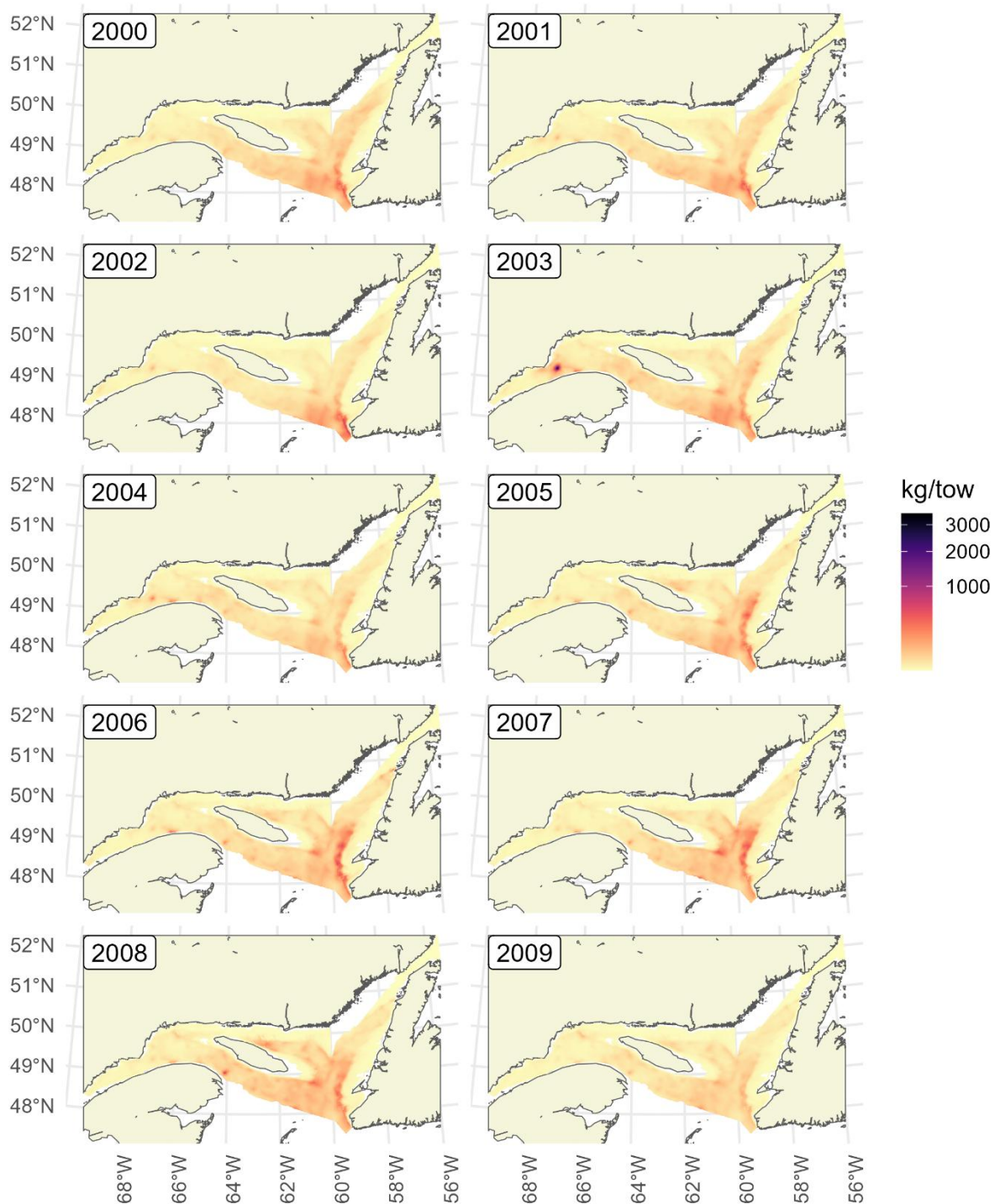


Figure 11: Predictions of Redfish density from the spatiotemporal model for the Estuary and the Gulf of St. Lawrence in August, between 2000 et 2009.

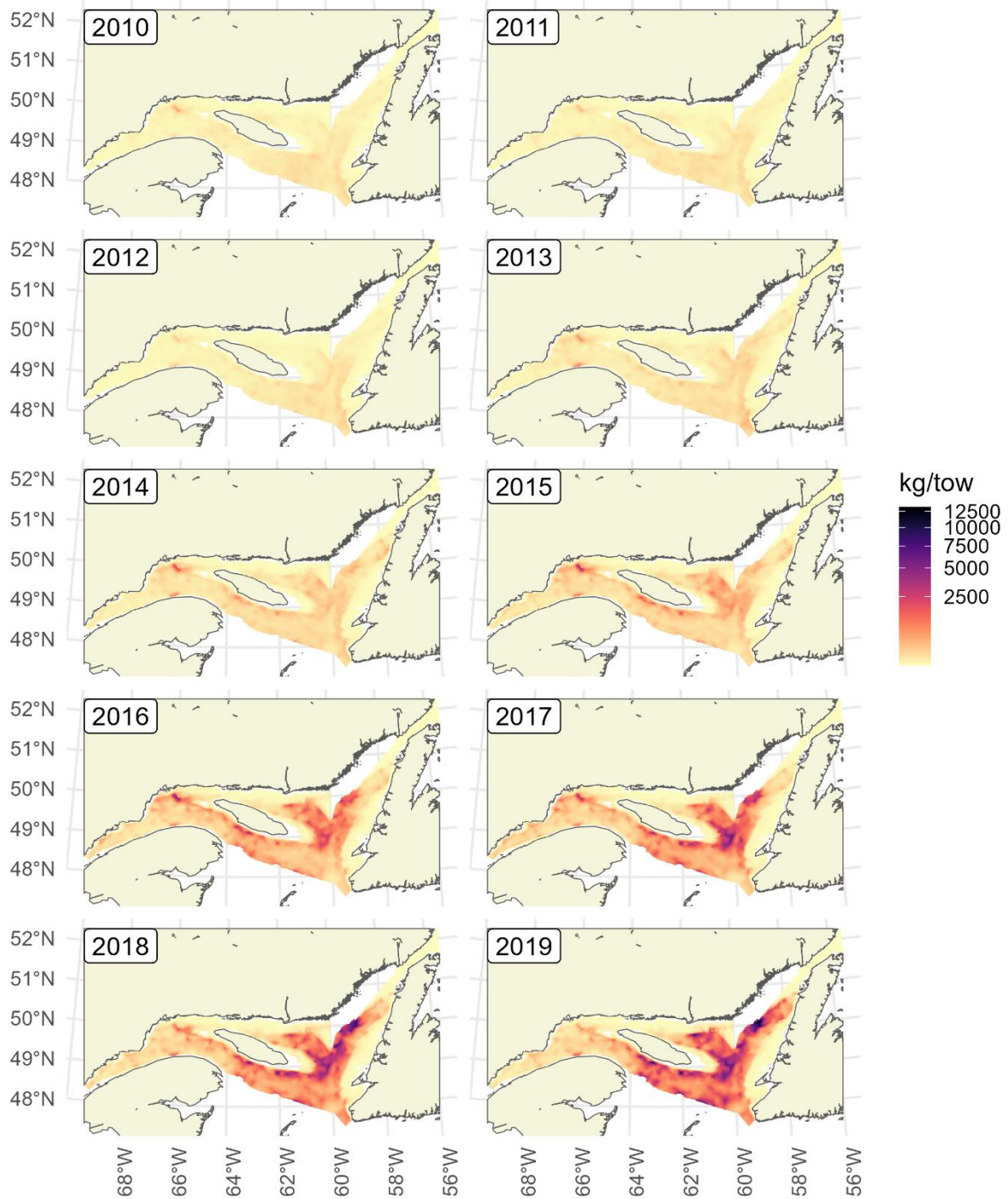


Figure 12: Predictions of Redfish density from the spatiotemporal model for the Estuary and the Gulf of St. Lawrence in August, between 2010 et 2019.

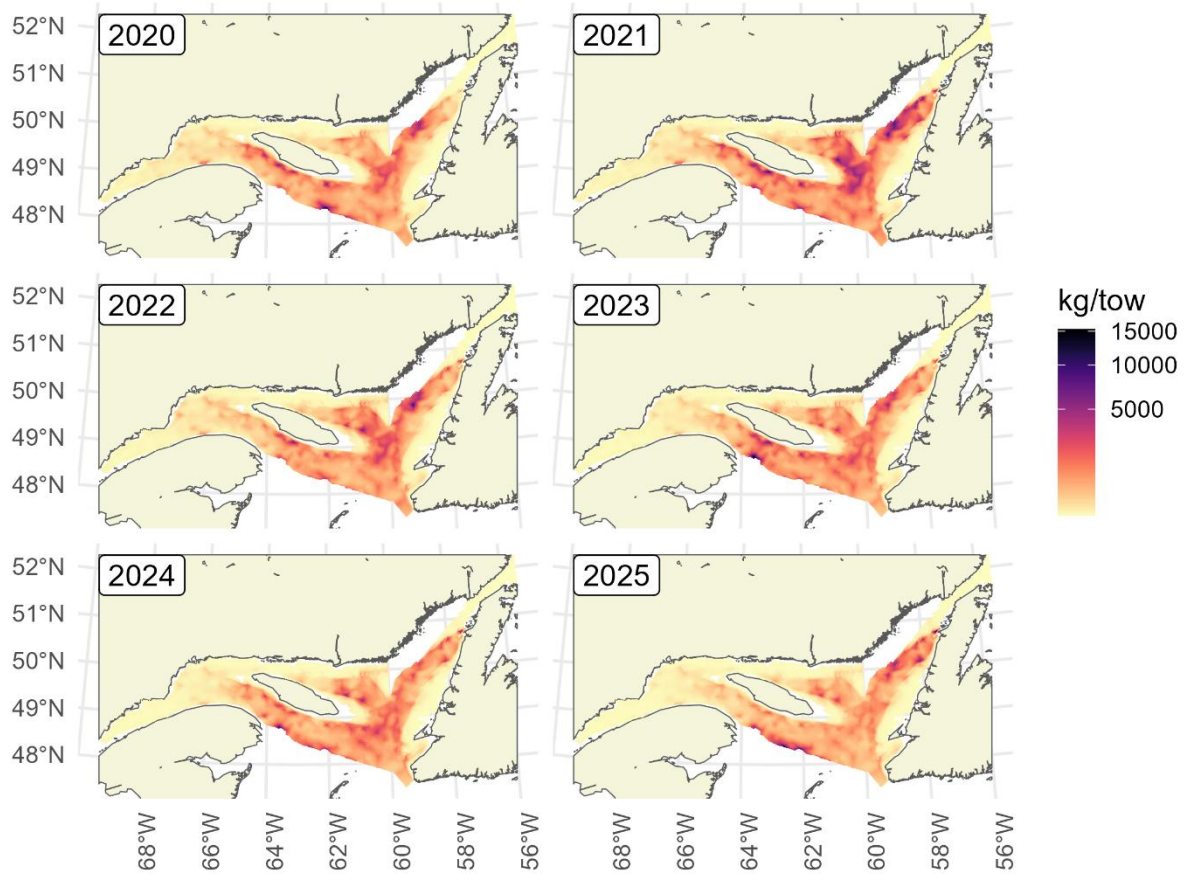


Figure 13: Predictions of Redfish density from the spatiotemporal model for the Estuary and Gulf of St. Lawrence in August, between 2020 et 2025.

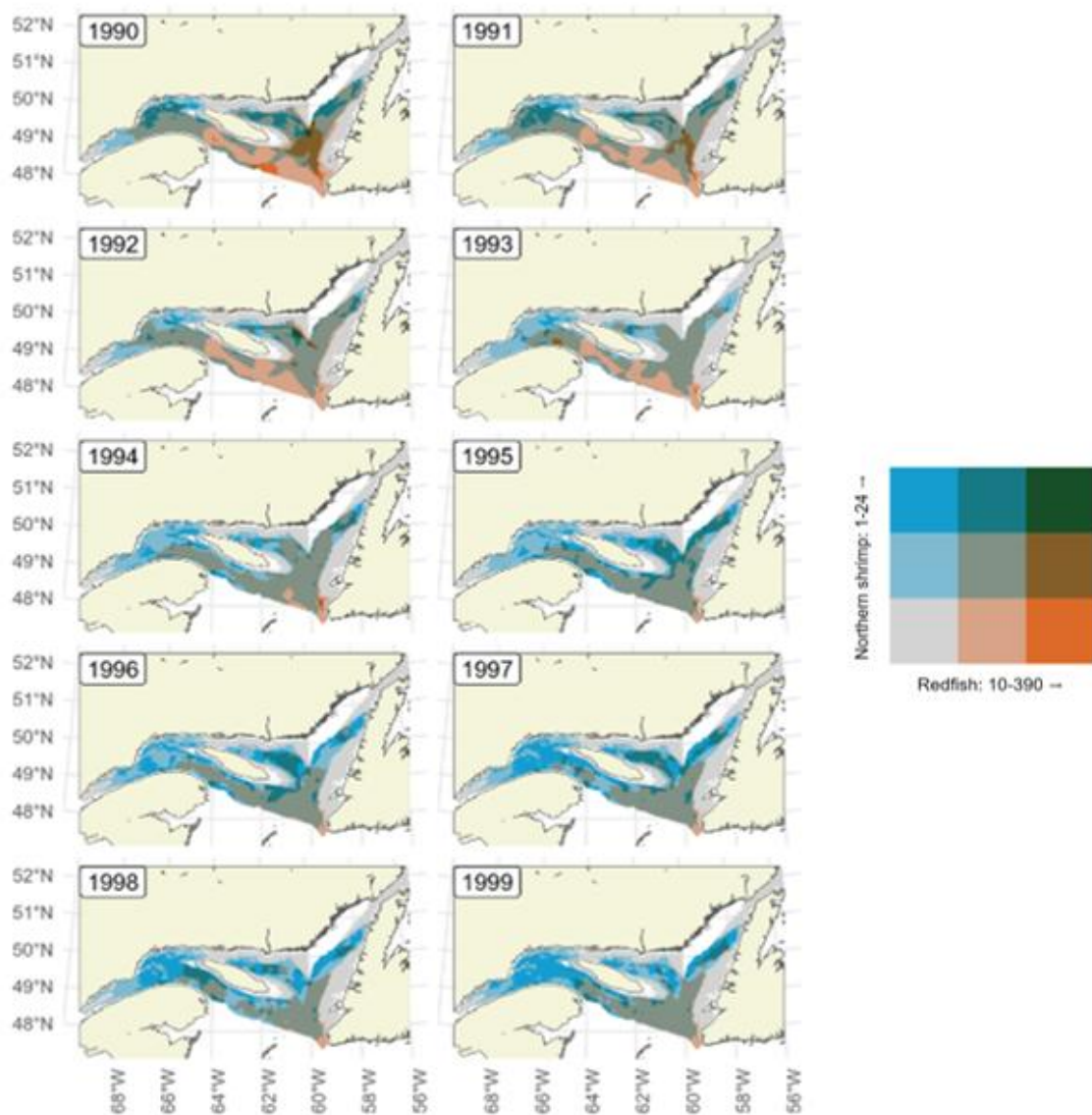


Figure 14: Overlap based on predicted density categories of Northern Shrimp and Redfish in the Estuary and Gulf of St. Lawrence from August 1990 to 1999. The colors correspond to the intersection of the density tertiles for Northern Shrimp and Redfish. For Northern Shrimp (on the vertical axis of the legend): 0–1 kg, 1–24 kg, 24 kg and over. For Redfish (on the horizontal axis): 0–10 kg, 10–390 kg, 390 kg and over.

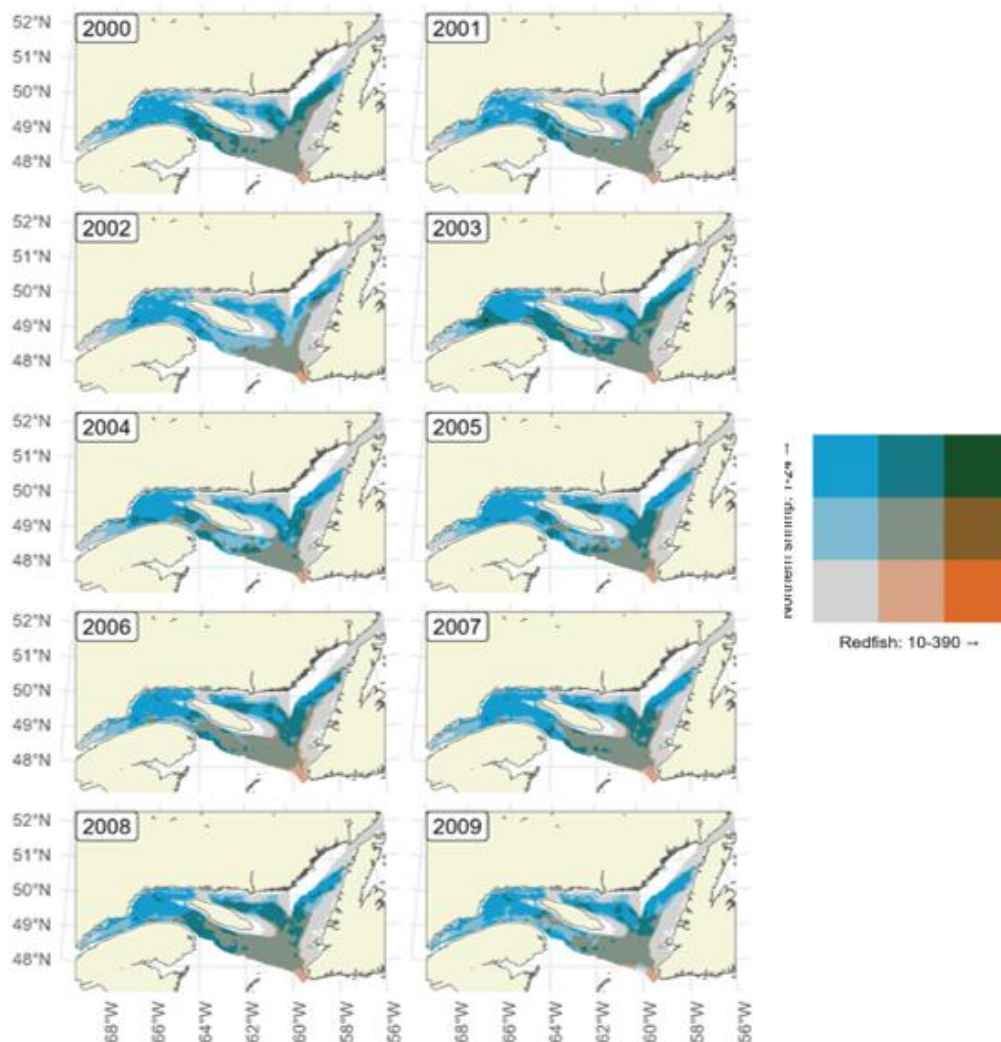


Figure 15: Overlap based on predicted density categories of Northern Shrimp and Redfish in the Estuary and the Gulf of St. Lawrence from August 2000 to 2009. The colors correspond to the intersection of the density tertiles for Northern Shrimp and Redfish. For Northern Shrimp (on the vertical axis of the legend): 0–1 kg, 1–24 kg, 24 kg and over. For Redfish (on the horizontal axis): 0–10 kg, 10–390 kg, 390 kg and over.

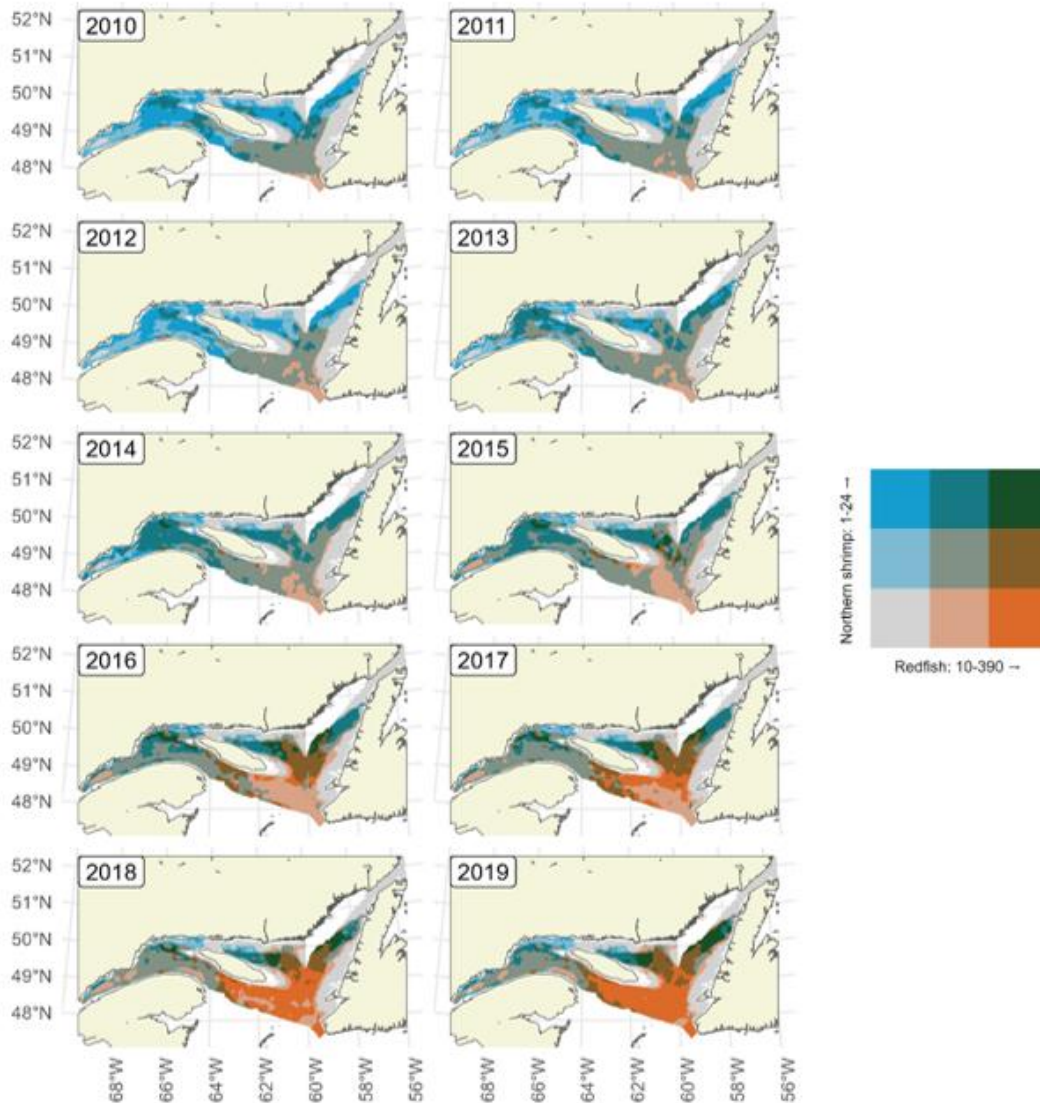


Figure 16: Overlap based on predicted density categories of Northern Shrimp and Redfish in the Estuary and the Gulf of St. Lawrence from August 2010 to 2019. The colors correspond to the intersection of the density tertiles for Northern Shrimp and Redfish. For Northern Shrimp (on the vertical axis of the legend): 0–1 kg, 1–24 kg, 24 kg and over. For Redfish (on the horizontal axis): 0–10 kg, 10–390 kg, 390 kg and over.

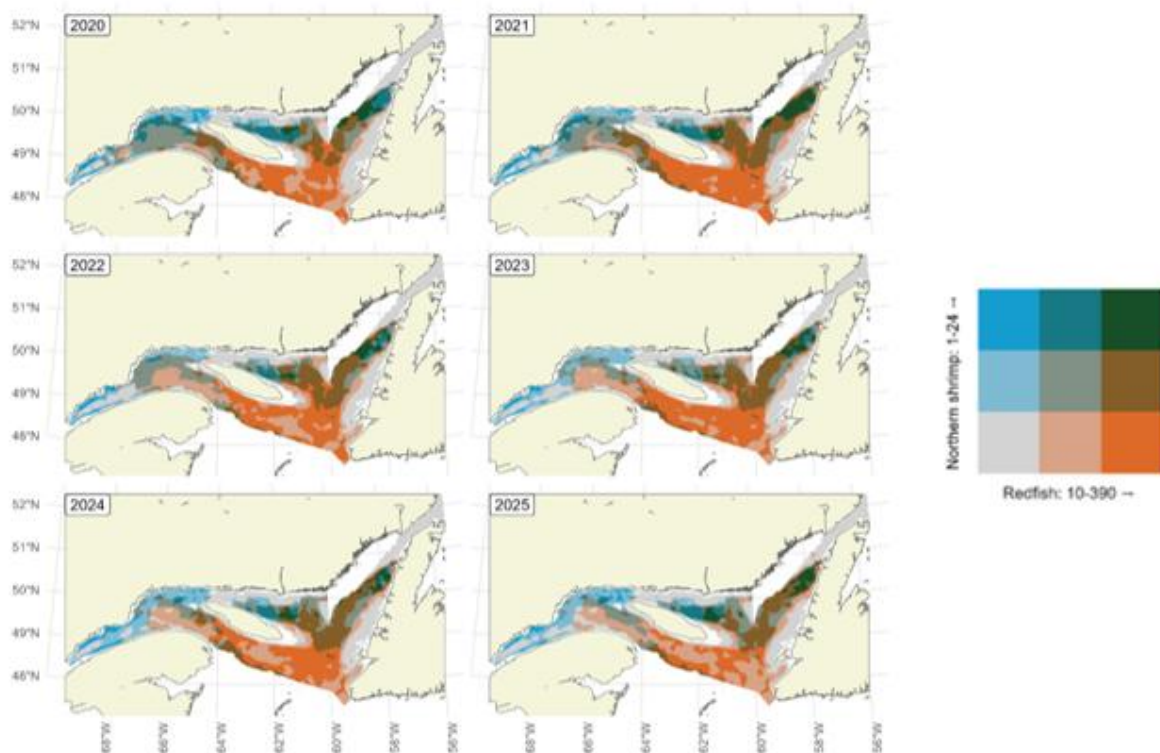


Figure 17: Overlap based on predicted density categories of Northern Shrimp and Redfish in the Gulf of St. Lawrence from August 2020 to 2025. The colors correspond to the intersection of the density tertiles for Northern Shrimp and Redfish. For Northern Shrimp (on the vertical axis of the legend): 0–1 kg, 1–24 kg, 24 kg and over. For Redfish (on the horizontal axis): 0–10 kg, 10–390 kg, 390 kg and over.

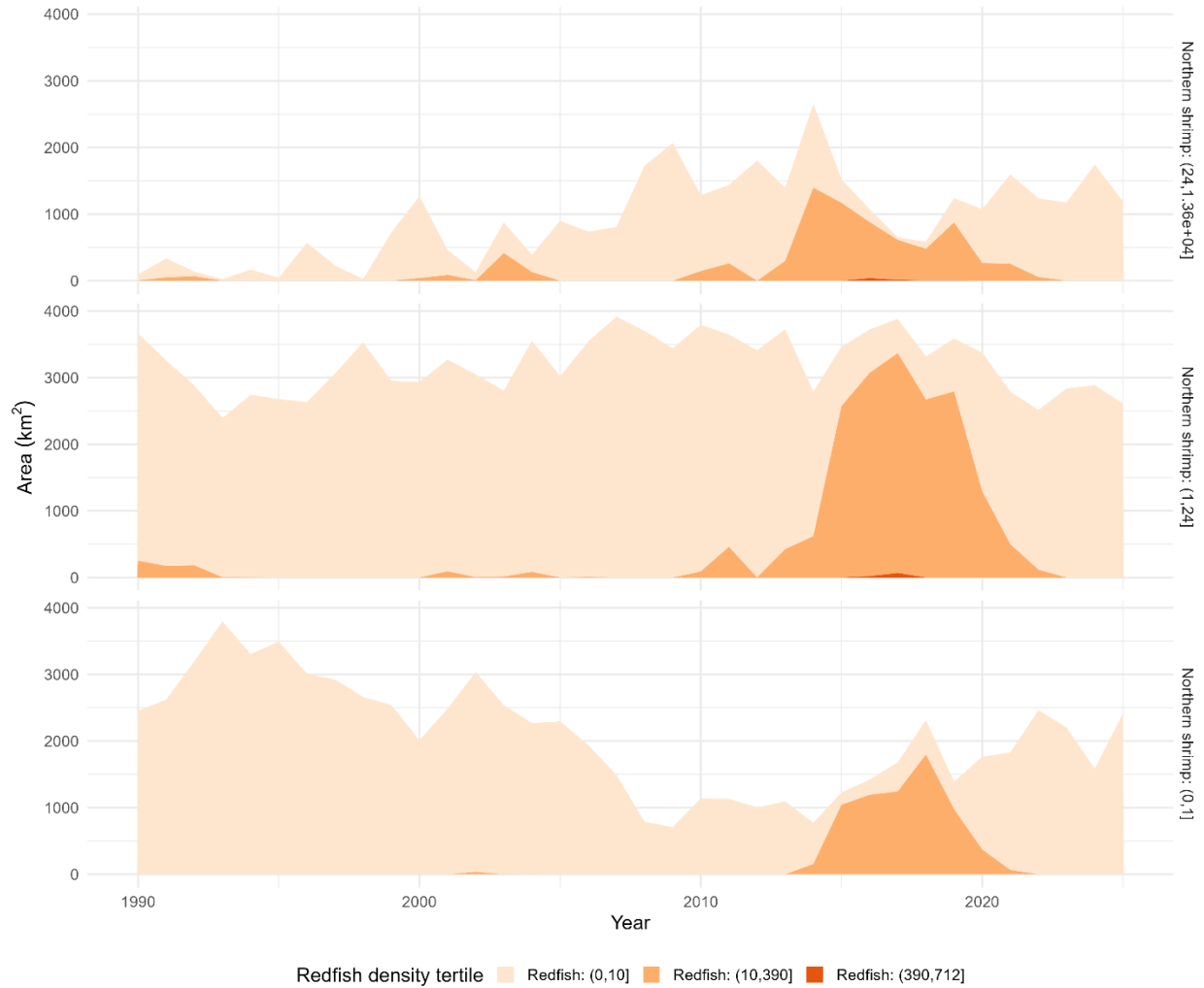


Figure 18: Area of the density tertiles for Northern Shrimp and Redfish in the Estuary zone by year. The top panel shows the area of high Northern Shrimp density, the middle panel shows medium density, and the bottom panel shows low density.

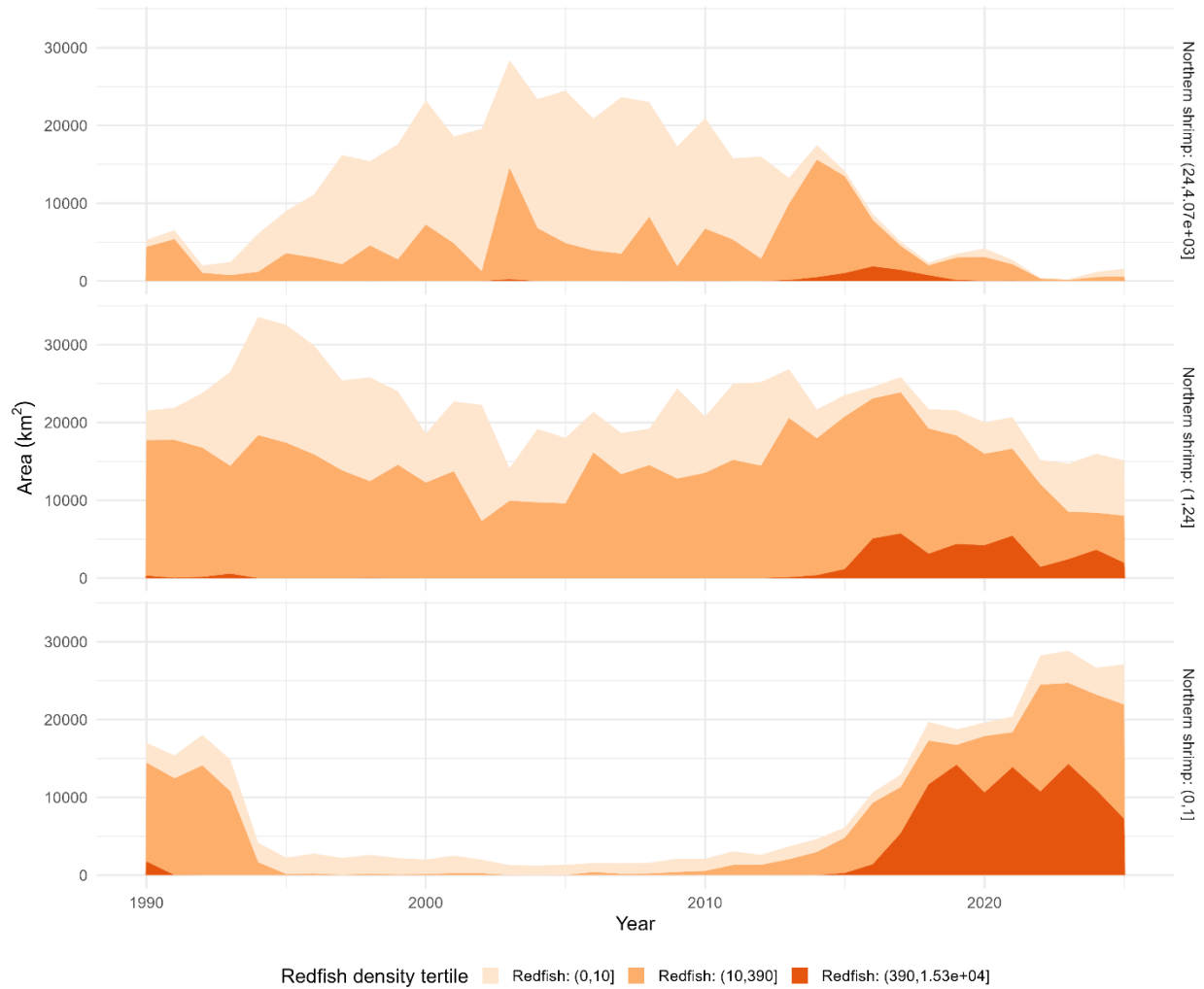


Figure 19: Area of the density tertiles for Northern Shrimp and Redfish in the Sept-Île zone by year. The top panel shows the area of high Northern Shrimp density, the middle panel shows medium density, and the bottom panel shows low density.

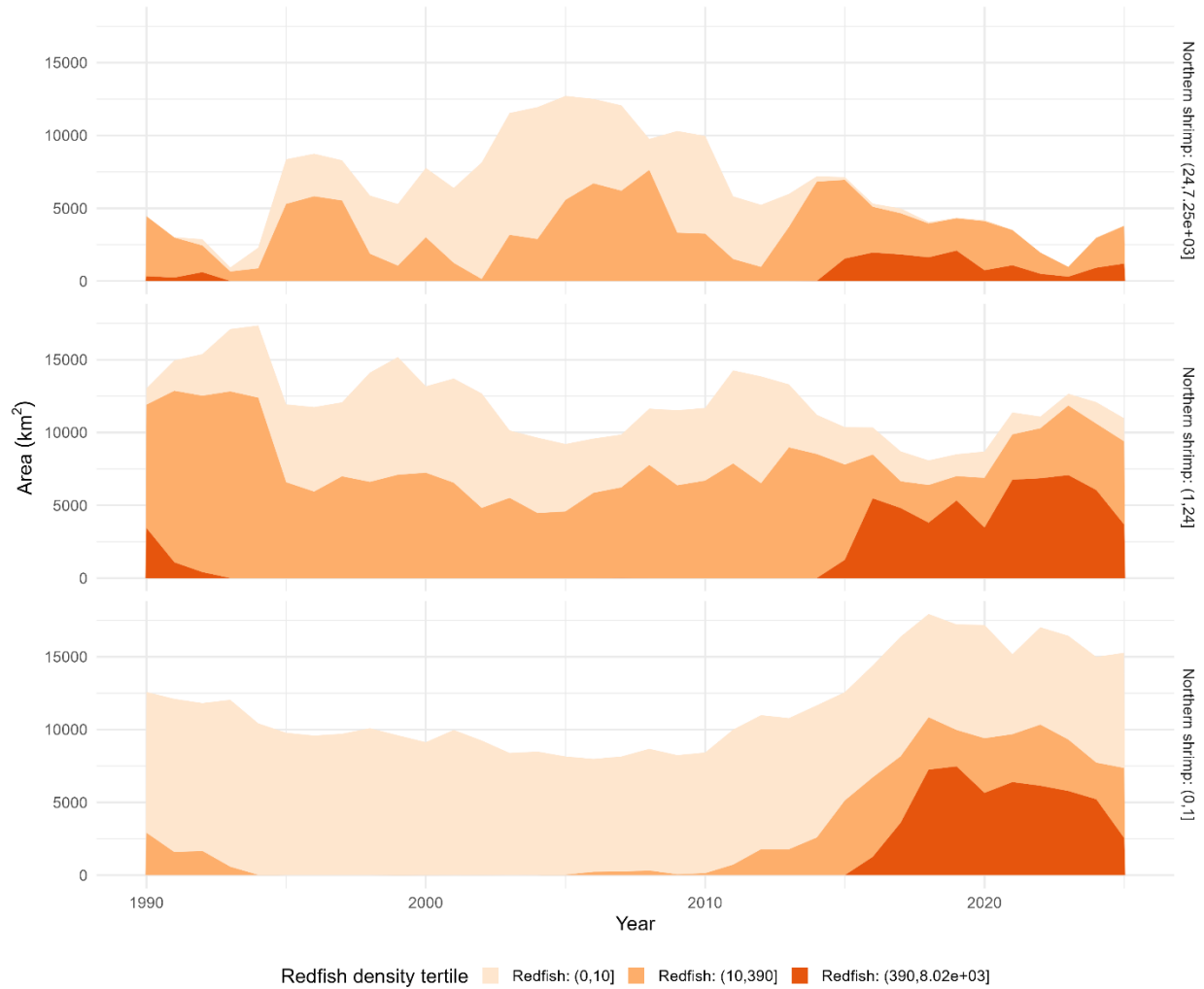


Figure 20: Area of the density tertiles for Northern Shrimp and Redfish in the Anticosti zone by year. The top panel shows the area of high Northern Shrimp density, the middle panel shows medium density, and the bottom panel shows low density.

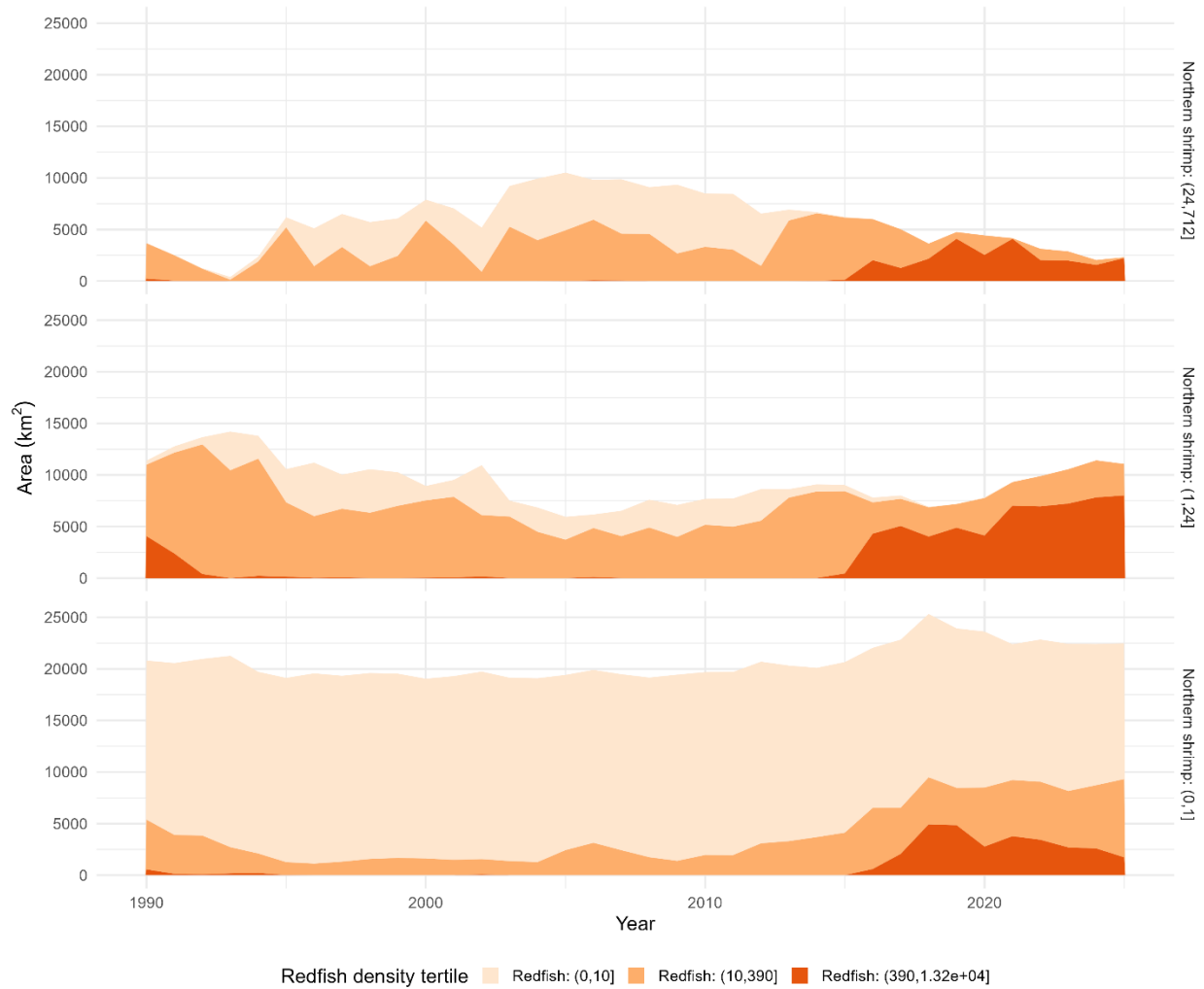


Figure 21: Area of the density tertiles for Northern Shrimp and Redfish in the Esquiman zone by year. The top panel shows the area of high Northern Shrimp density, the middle panel shows medium density, and the bottom panel shows low density.

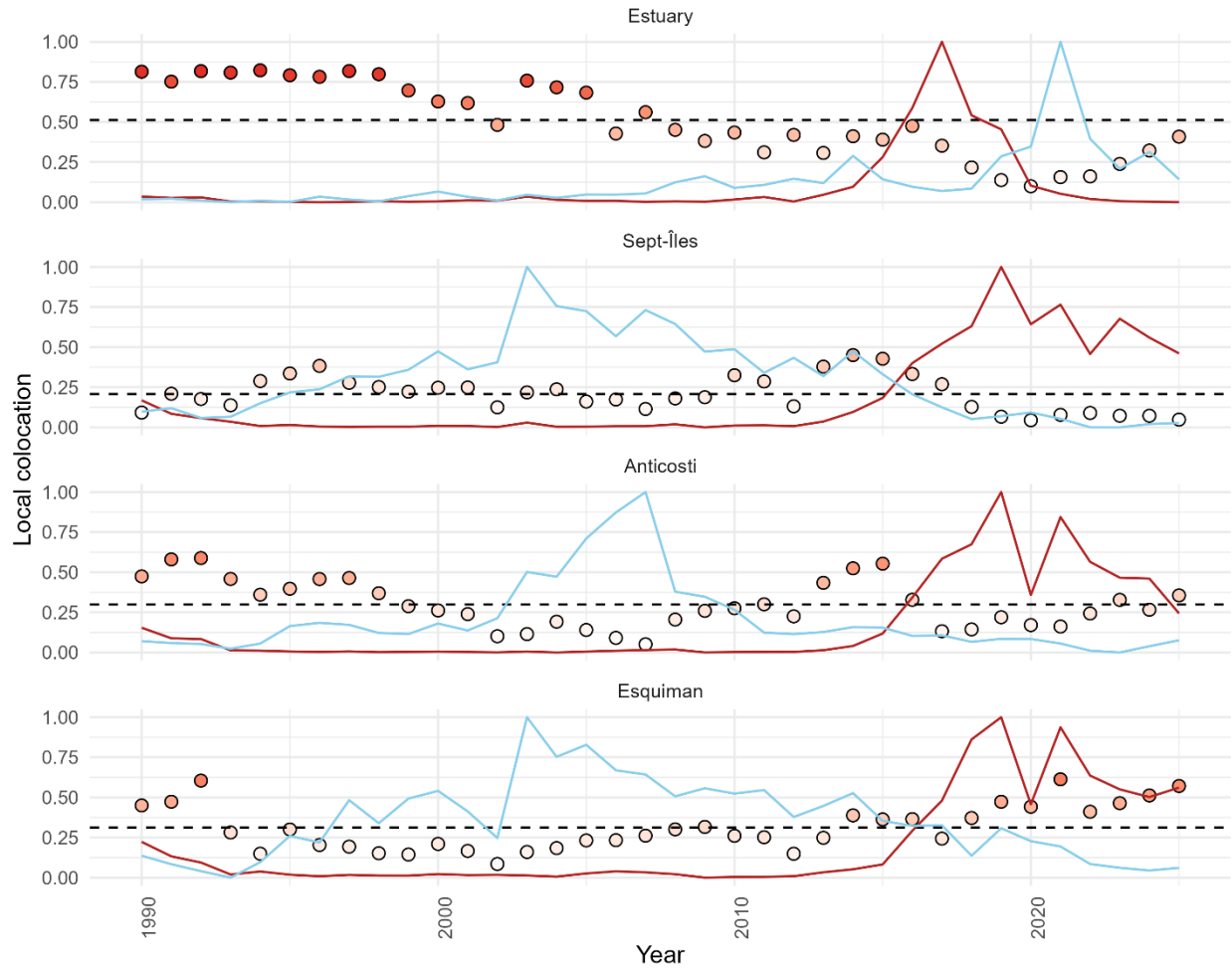


Figure 22: Local collocation index calculated by year and by Northern Shrimp stock assessment area based on predictions from spatiotemporal models for Northern Shrimp and Redfish. The dashed line represents the average local collocation index over the study period for each area. The color of the points corresponds to their value. The blue and red lines represent the average density, rescaled between 0 and 1 for each zone, of Northern Shrimp and Redfish, respectively.

APPENDIX A : CROSS-VALIDATION RESULTS

Table A-1: Cross-validation results for Northern Shrimp density models.

Models (fixed effects)	Sum of likelihood	Root mean squared error	*AIC	*Delta AIC
1- Depth + year	-20366.24	41.98	38990.72	161.58
2- Depth + temperature + year	-20329.62	41.71	38858.33	29.19
3 - Depth * temperature + year	-20216.33	42.87	38829.14	0.00

** The AIC was calculated for the entire dataset, that is, independent of the cross-validation process.*

Cross-validation for Northern Shrimp suggests either Model 2 or Model 3, depending on the performance metric used (either the sum of likelihood or the root mean square error). We selected Model 3 because the sum of likelihood is the preferred performance metric in the sdmTMB methodology (see Anderson et al. 2026).

Table A-2: Cross-validation results for northern Redfish density models.

Models (fixed effects)	Sum of likelihood	Root mean squared error	*AIC	*Delta AIC
1- Depth + year	-30889.74	522.07	53728.52	108.50
2- Depth + temperature + year	-30872.67	517.03	53649.23	29.22
3 - Depth * temperature + year	-30769.17	512.08	53620.02	0.00

** The AIC was calculated for the entire dataset, that is, independent of the cross-validation process.*

Cross-validation suggests that Model 3 improves the quality of predictions for Redfish.

APPENDIX B : DIAGNOSIS OF SPATIOTEMPORAL MODELS

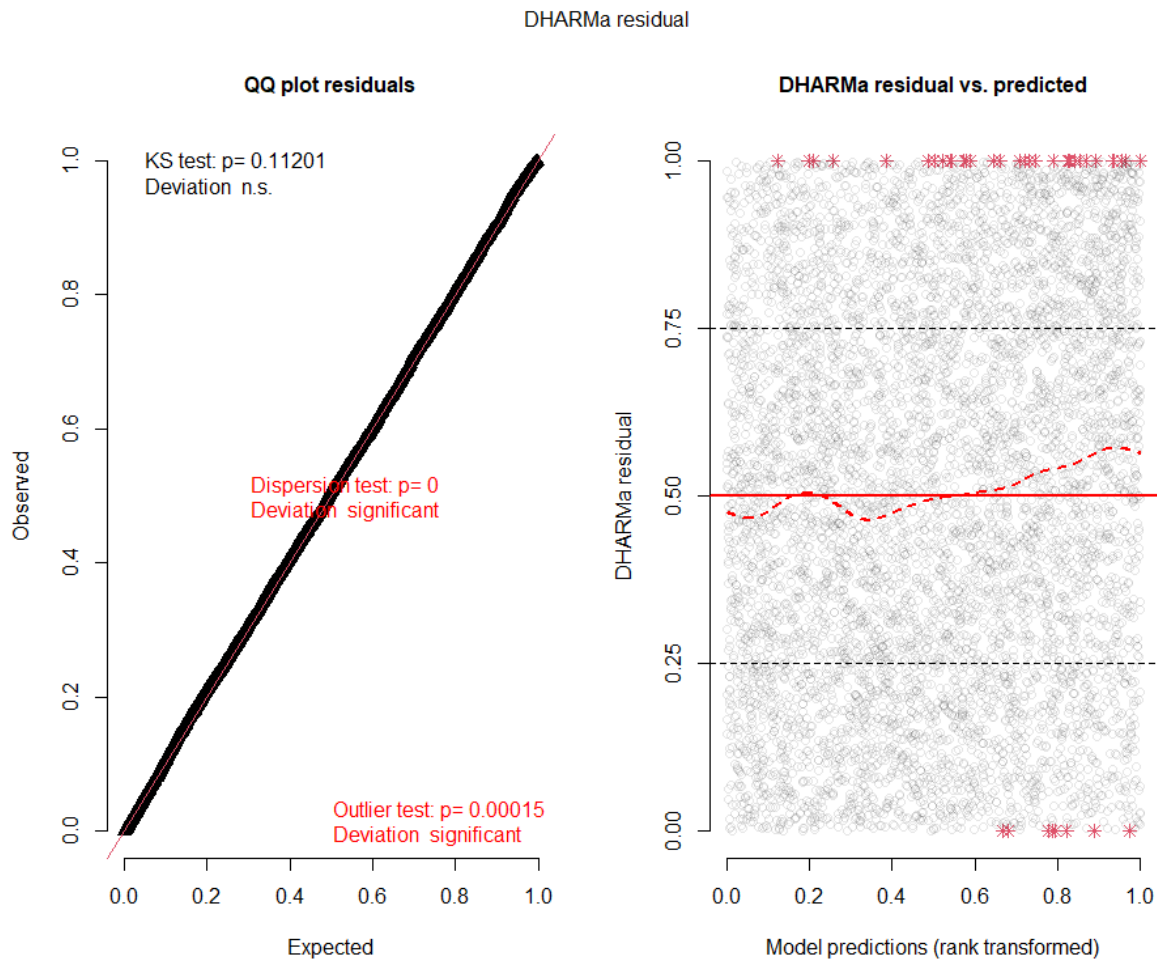


Figure B-1: Distribution of residuals from the spatiotemporal model of Northern Shrimp: quantile-quantile plot (left) and DHARMa residuals (simulated) on the right.

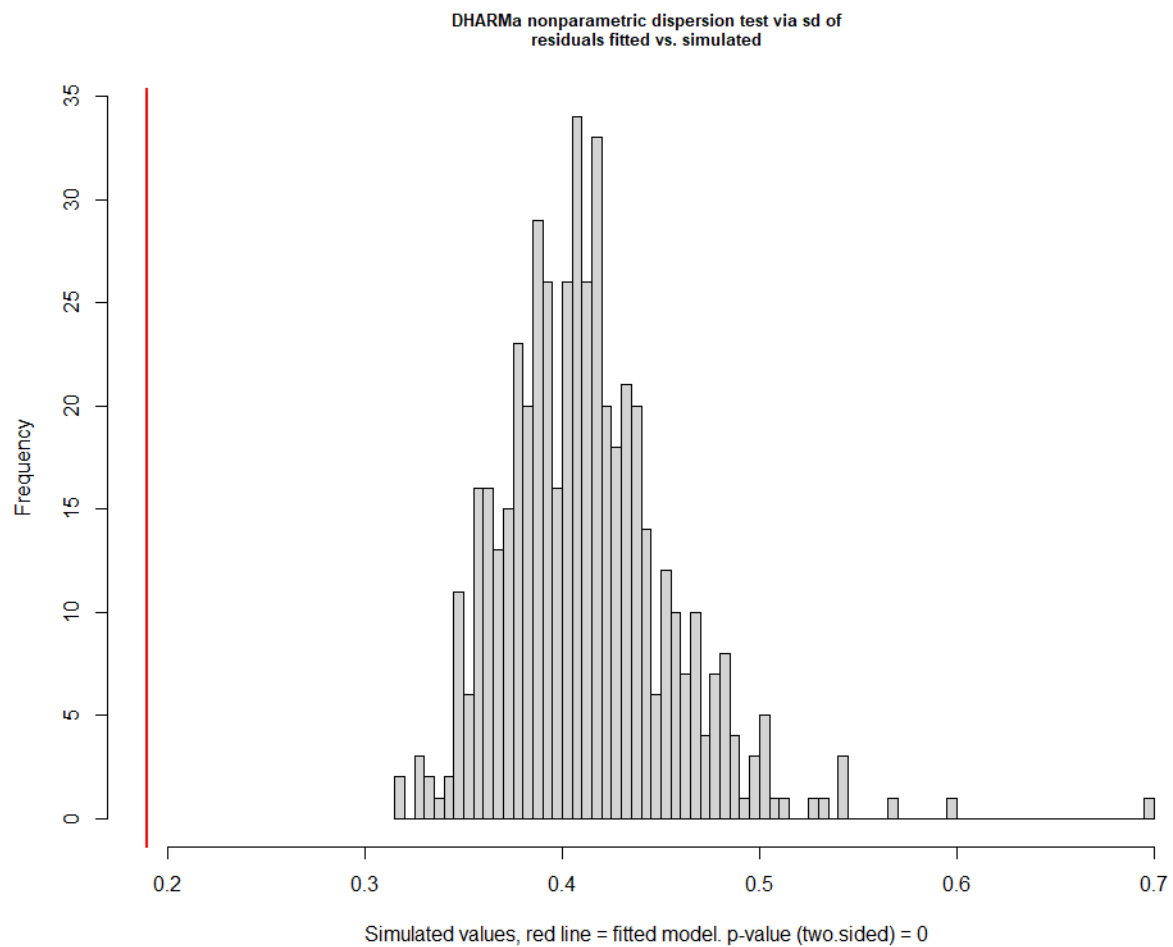


Figure B-2: DHARMA overdispersion test of the spatiotemporal model for Northern Shrimp.

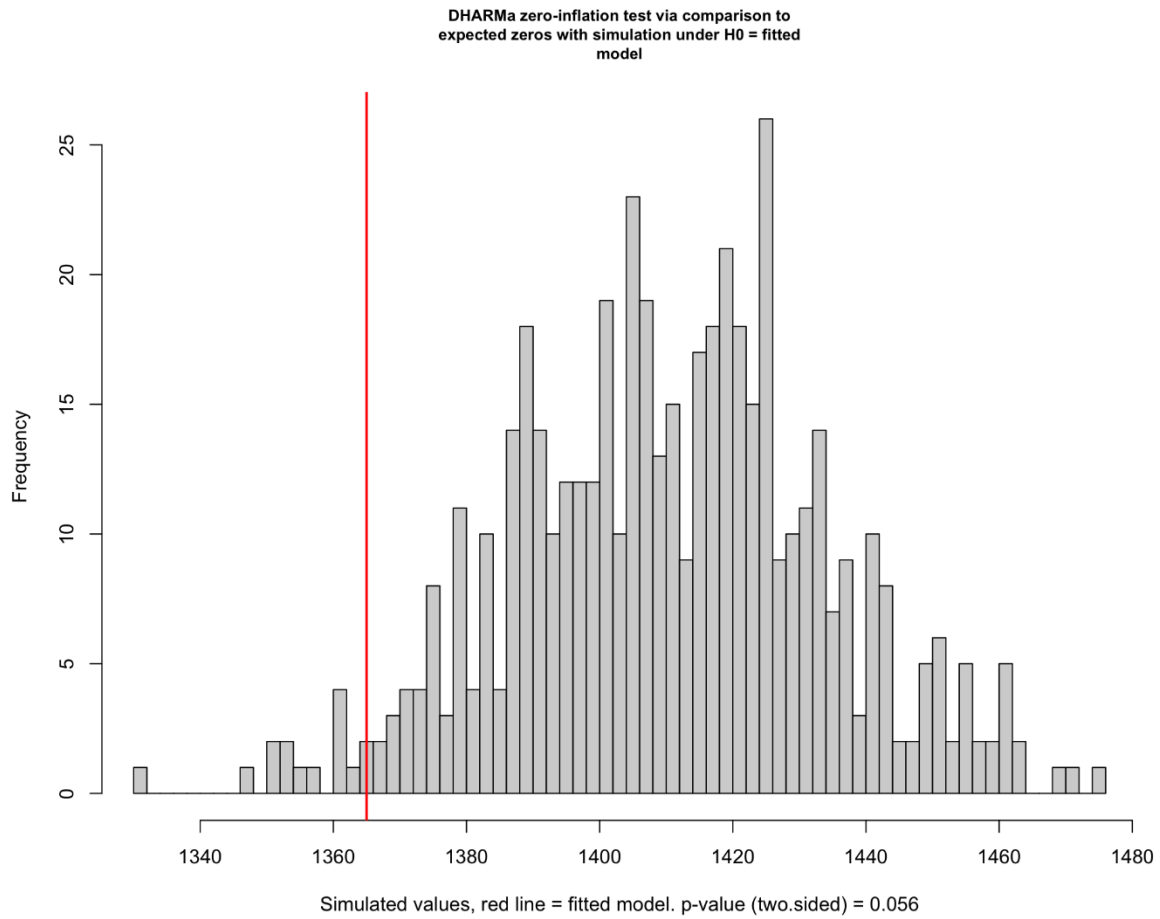


Figure B-3: Zero inflation test for the spatiotemporal model for Northern Shrimp.

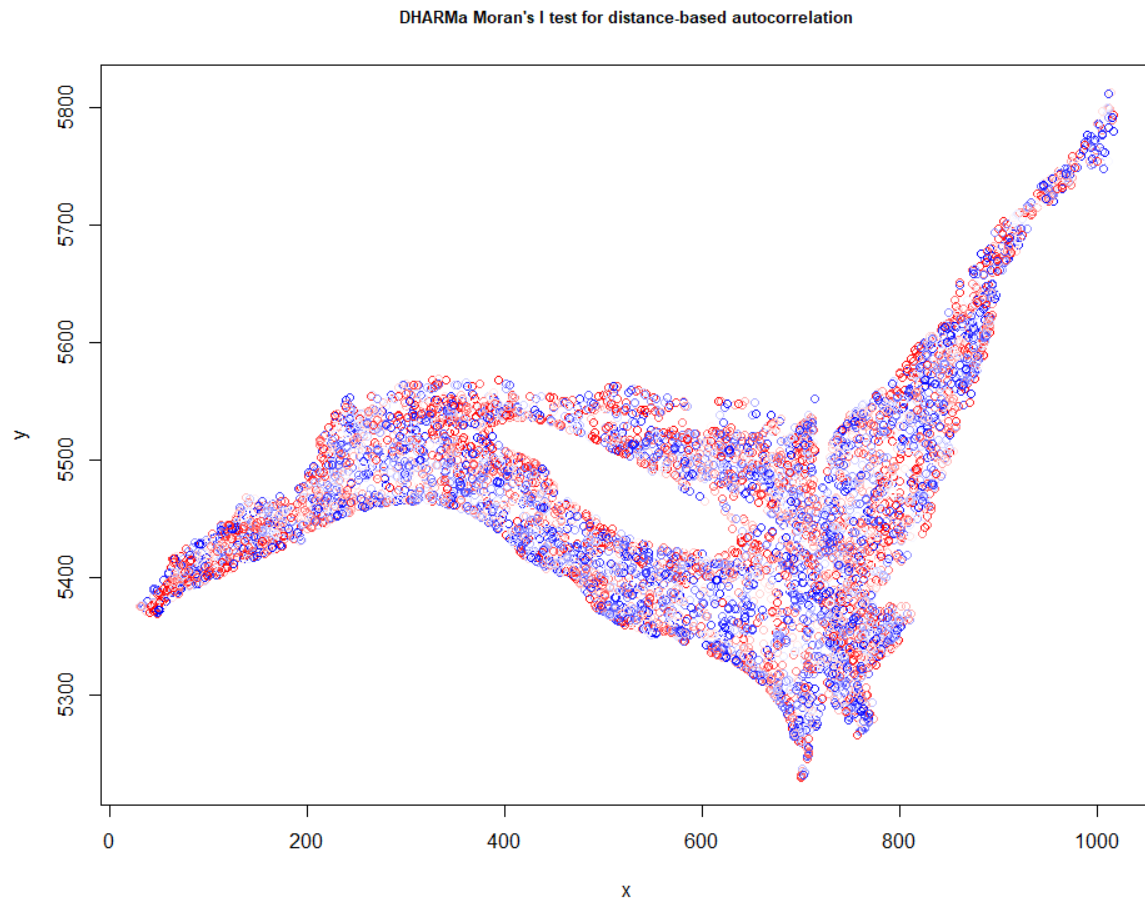


Figure B-4: Spatial distribution of DHARMA residuals (Moran's I spatial autocorrelation test: p -value = $3.173e-11$) from the spatiotemporal model of the Northern Shrimp. Red points represent overestimated values; blue points represent underestimated values.

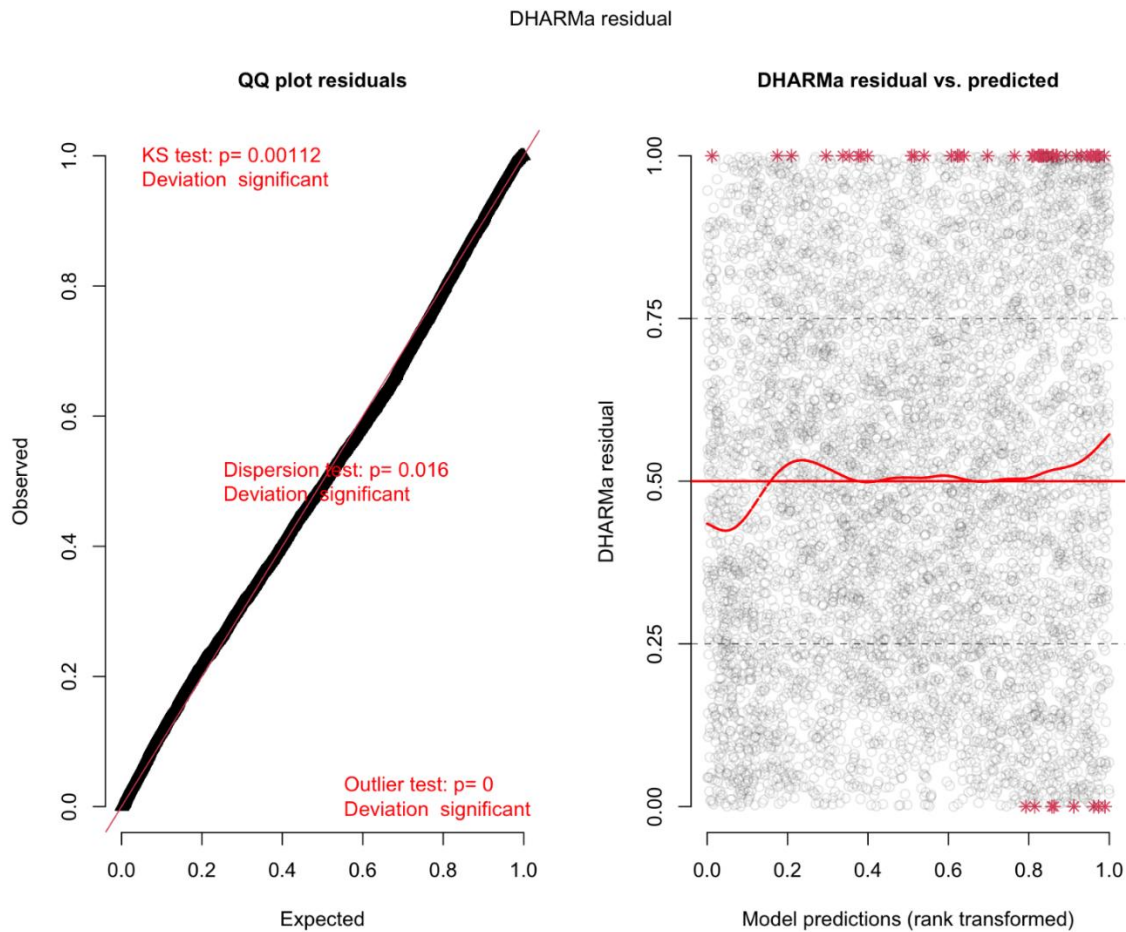


Figure B-5: Distribution of residuals from the spatiotemporal model of Redfish: quantile-quantile plot (left) and DHARMA residuals (simulated) on the right.

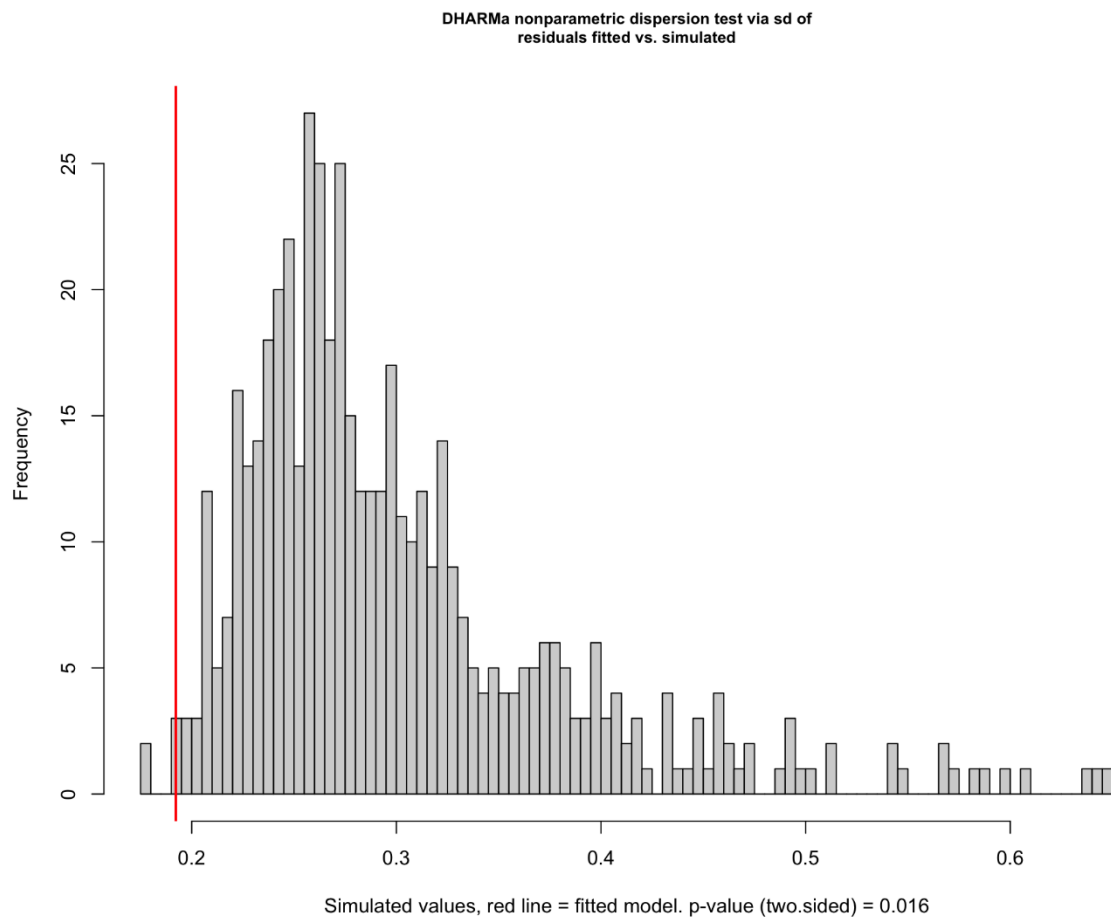


Figure B-6: DHARMA overdispersion test of the spatiotemporal model for Redfish.

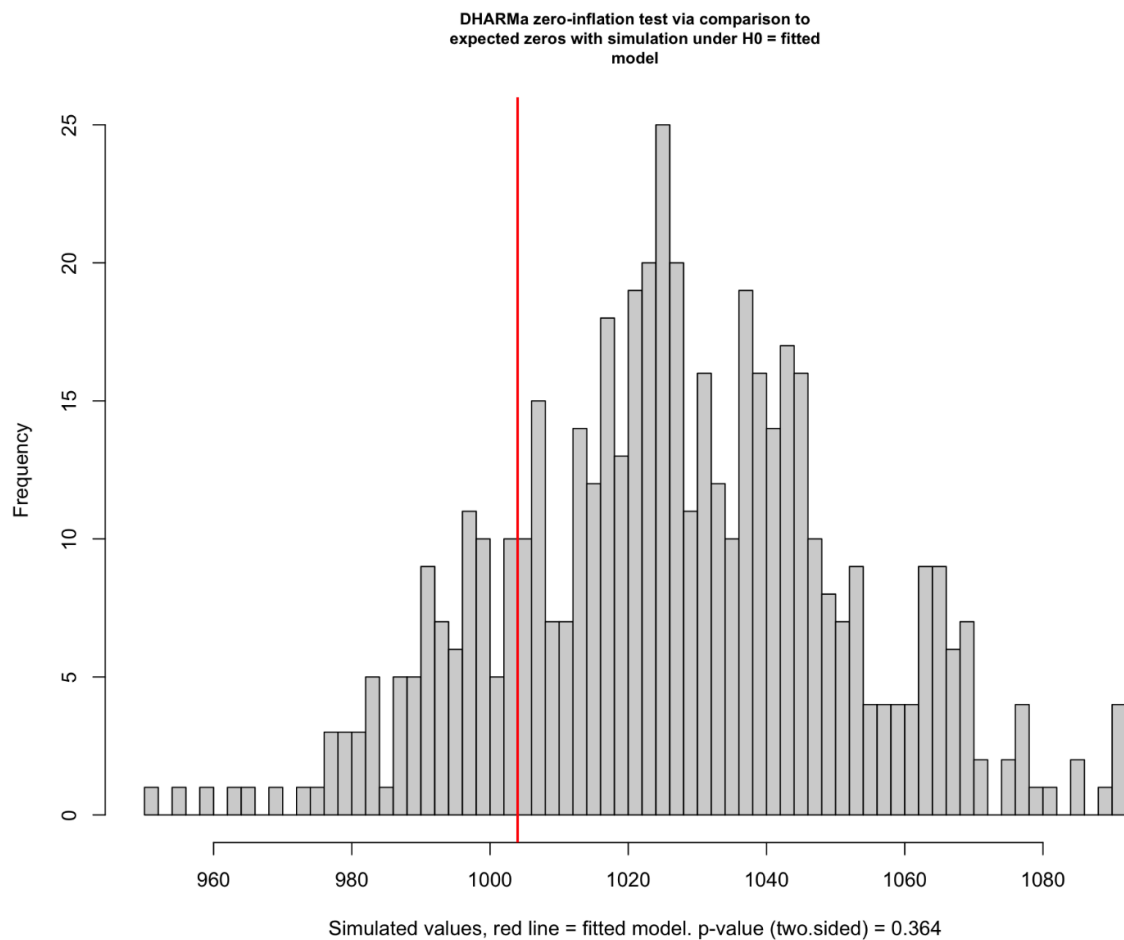


Figure B-7: Zero inflation test for the spatiotemporal model for Redfish.

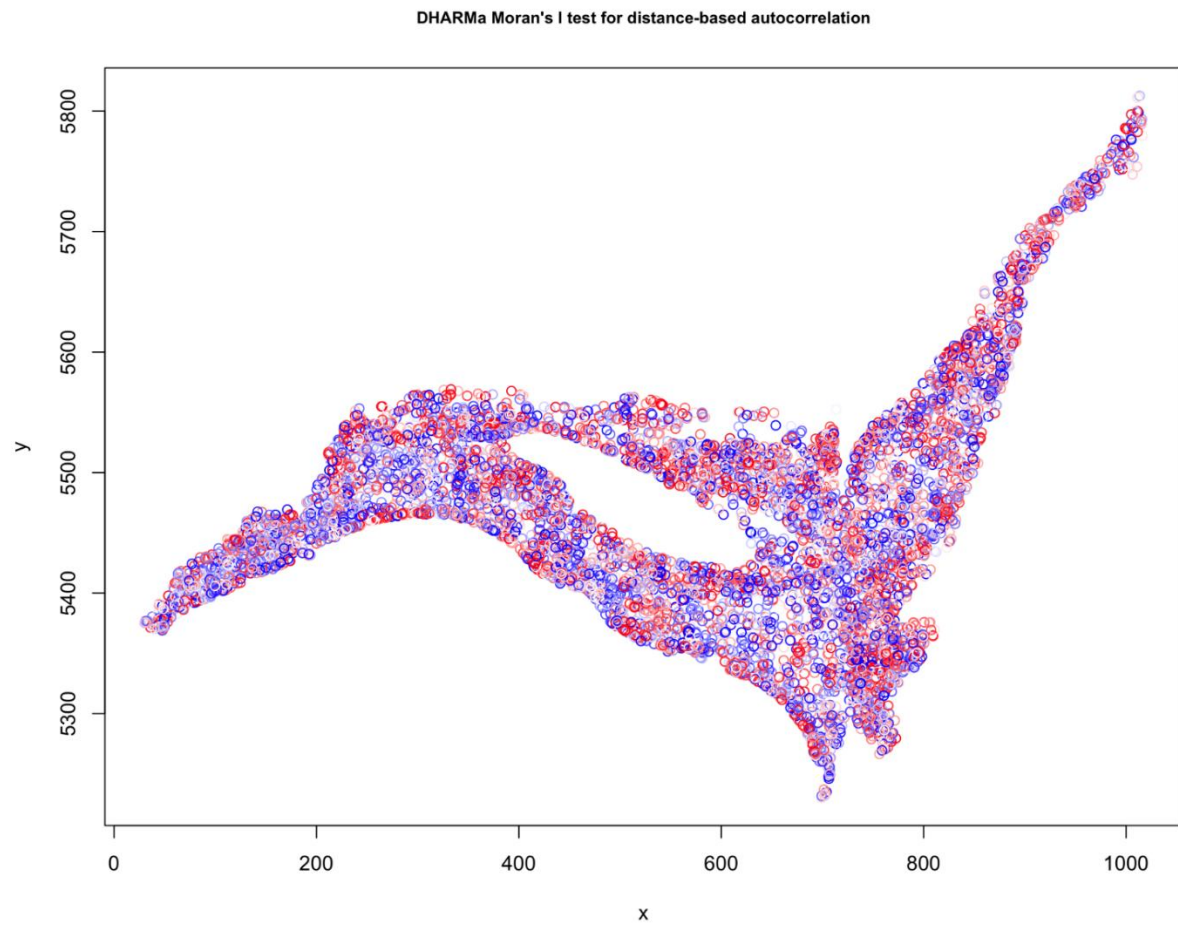


Figure B-8: Spatial distribution of DHARMa residuals (Moran's I spatial autocorrelation test: p -value = $3.173e-11$) from the spatiotemporal model of Redfish. Red points represent overestimated values; blue points represent underestimated values.

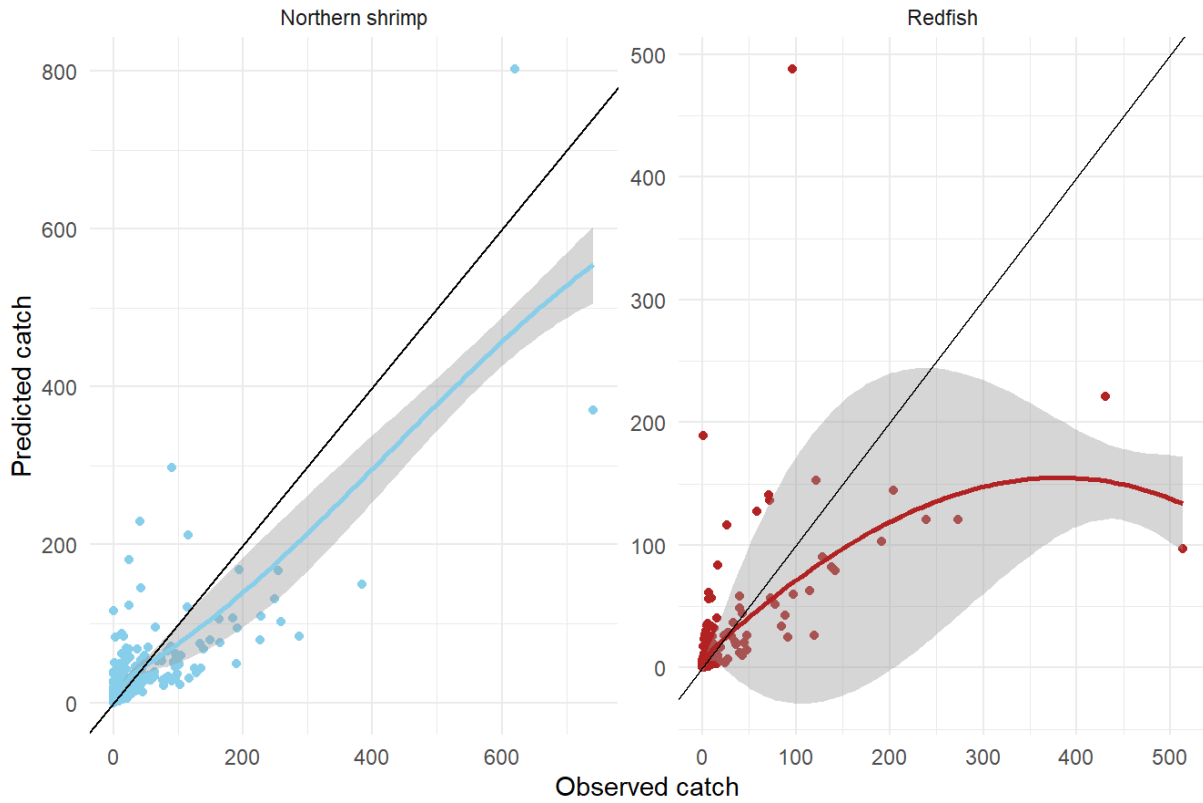


Figure B-9: Comparison of observed catch values (kg) and predicted values (kg) based on spatiotemporal models for Northern Shrimp (left panel, in blue, $R^2_{adj}=0.6261$) and Redfish (right panel, in red, $R^2_{adj}=0.3819$) in the Estuary zone. The black line has a slope of 1 and a y-intercept of 0. The shaded area represents the 95% confidence interval.

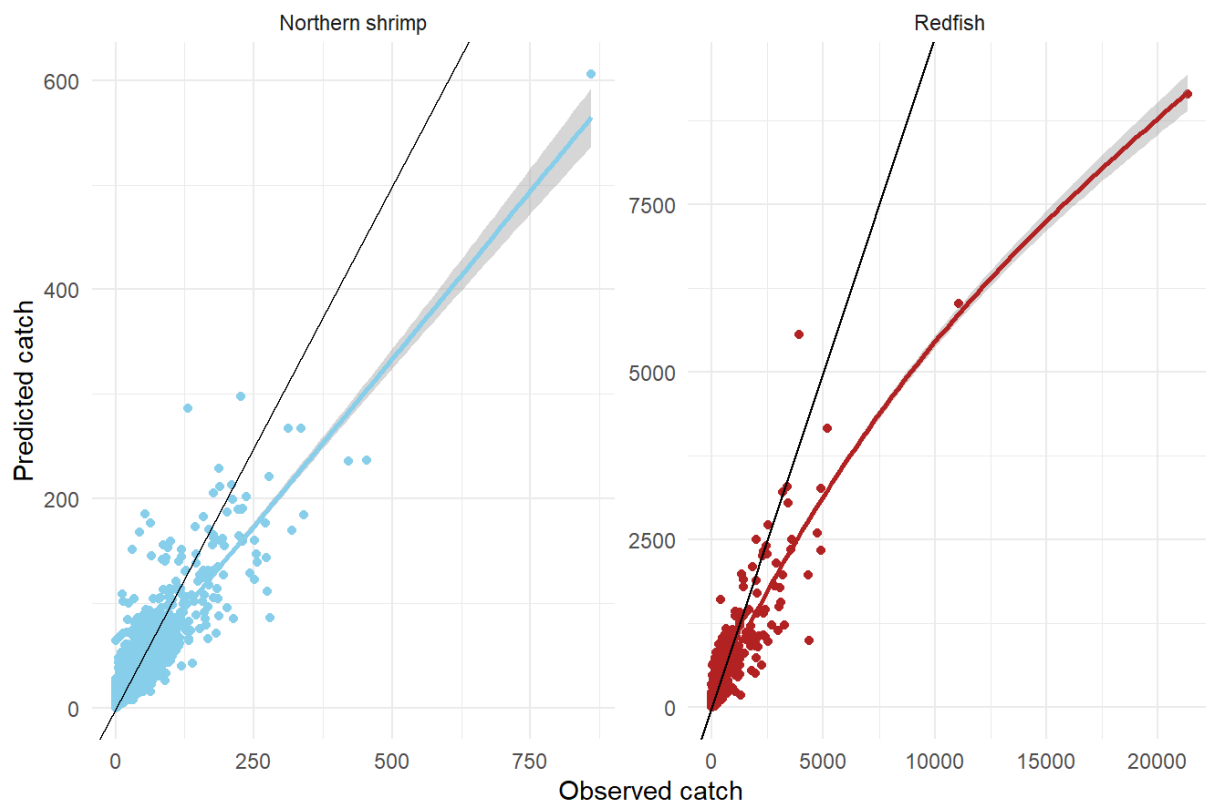


Figure B-10: Comparison of observed density values (kg) and predicted values (kg) based on spatiotemporal models for Northern Shrimp (left panel, in blue, $R^2_{adj}=0.8050$) and Redfish (right panel, in red, $R^2_{adj}=0.8364$) in the Sept-Îles zone. The black line has a slope of 1 and a y-intercept of 0. The shaded area represents the 95% confidence interval.

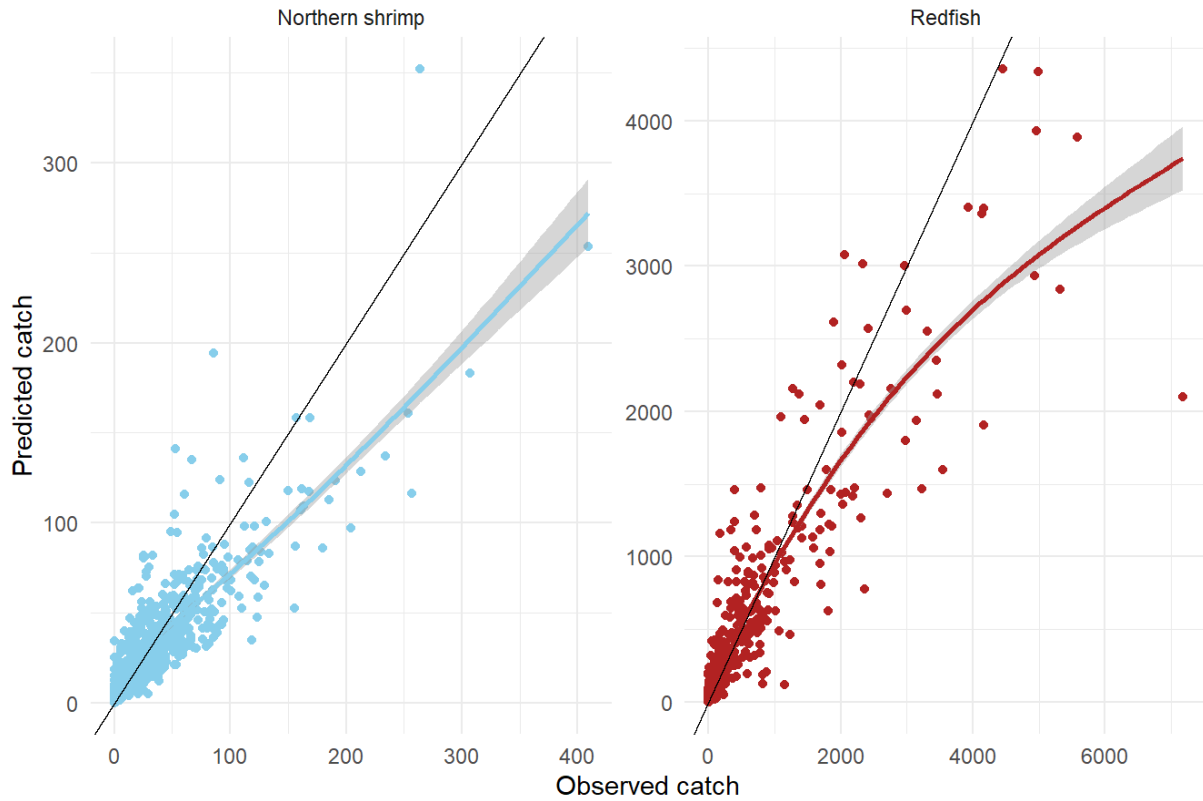


Figure B-11: Comparison of observed density values (on the x-axis) and predicted values (on the y-axis) based on spatiotemporal models for Northern Shrimp (left panel, in blue, $R^2_{adj}=0.7739$) and Redfish (right panel, in red, $R^2_{adj}=0.8393$) in the Anticosti zone. The black line has a slope of 1 and a y-intercept of 0. The shaded area represents the 95% confidence interval.

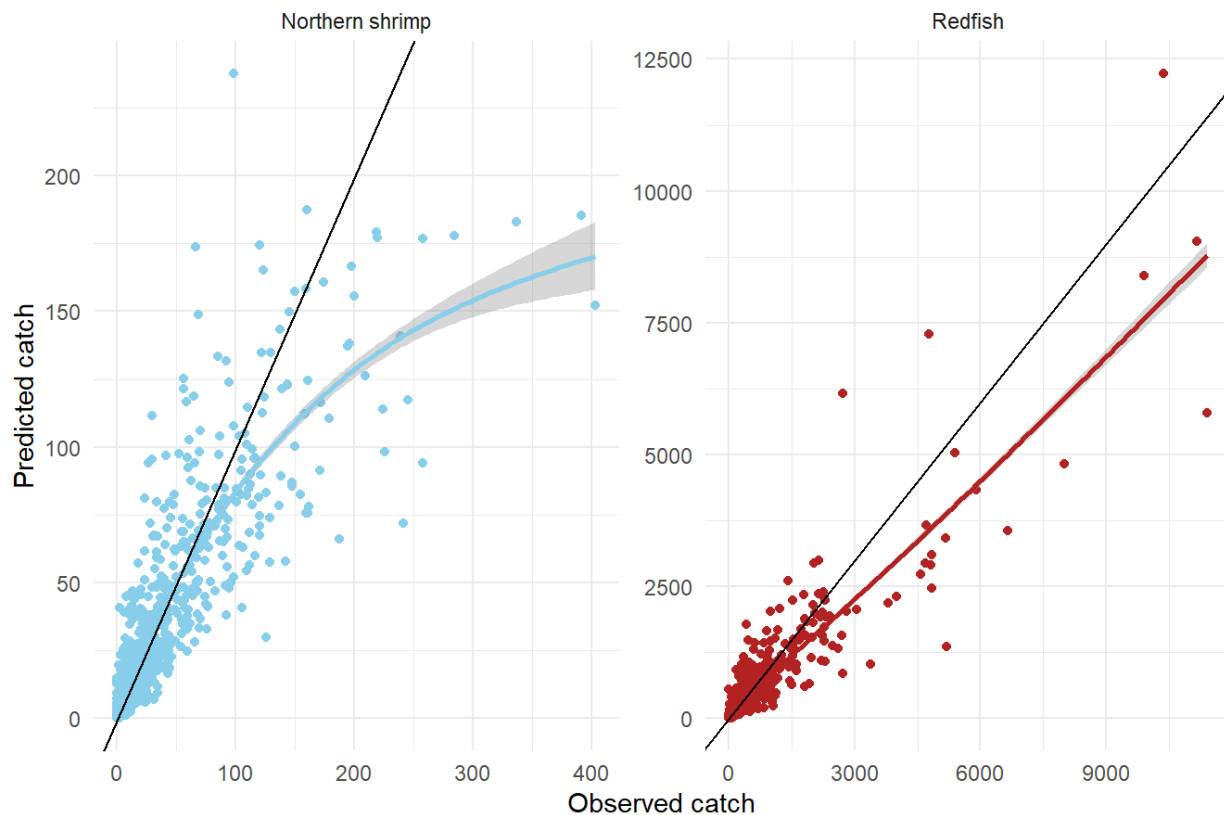


Figure B-12: Comparison of observed density values (x-axis) and predicted values (y-axis) based on spatiotemporal models for Northern Shrimp (left panel, in blue, $R^2_{adj}=0.7841$) and Redfish (right panel, in red, $R^2_{adj}=0.8449$) in the Esquiman zone. The black line has a slope of 1 and a y-intercept of 0. The shaded area represents the 95% confidence interval.