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Seasonal distribution and concentration of four baleen whale species in the St. Lawrence Estuary based on 22 years of DFO observation data

Arnaud Mosnier, Jean-François Gosselin and Véronique Lesage

Maurice-Lamontagne Institute,
Fisheries and Oceans Canada,
P.O. Box 1000,
Mont Joli, Quebec, G5H 3Z4

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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

The Estuary and the Gulf of St. Lawrence are feeding grounds for several North Atlantic whales, including minke, humpback, endangered blue whales and fin whales which are designated by COSEWIC as Special Concern. The St. Lawrence is an important shipping route and vessel strikes are an important source of mortality for these species. The development of efficient protection measures requires knowledge about their spatial and temporal distribution. Observations of these species collected during aerial and boat surveys conducted between 1995 to 2017 were used to produce maps presenting raw sightings, relative densities from kernel analyses and predicted relative probability of occurrence from spatial distribution modelling. The latter allowed a more complete use of the data available, while reducing biases linked to survey coverage, and the resulting maps are considered to be the best representation of spatial distribution of the four baleen whales in the Estuary. The models predict a higher probability of fin, humpback and minke whale occurrence at the head of the Laurentian Channel. A higher probability of blue, fin and humpback whale occurrence is also predicted along the slopes of the Laurentian Channel, while a higher probability of minke whale occurrence is predicted along the shallow water slopes near the 20 m isobath. Finally, a higher probability of blue whale occurrence is also predicted in the deeper waters of the Laurentian Channel between Les Escoumins and Forestville. These maps highlight potentially important zones to be considered when defining management plans aiming to reduce risks of vessel strikes.

INTRODUCTION

Canadian Atlantic waters, and in particular the Estuary and the Gulf of St. Lawrence, are a feeding ground for many North Atlantic species of whales, including the endangered blue whale and the fin whale which is designated as Special Concern (COSEWIC 2002, 2005). The St. Lawrence river is also an important shipping route with nearly four thousand ships transiting to Canada and United States each year. Ferries, pleasure boats and whale-watching vessels also contribute significantly to the ship traffic in the estuary (Chion et al. 2009) exposing whales to a potential risk of vessel strike. Vessel strike is considered to be an important source of mortality for several species of whales including humpback, fin, blue and minke whale (Jensen and Silber 2003). Long term management and recovery of those species rely on our knowledge about their distribution and our capacity to protect important habitats. The protection of marine mammals and their habitat is a primary objective of the Saguenay-St. Lawrence Marine Park. This would also be a primary objective of a larger Marine Protected Area planned in the St. Lawrence Estuary. Therefore, information on seasonal occurrence and distribution of blue, fin, humpback and minke whale was requested.

Between 1995 and 2017, the Department of Fisheries and Ocean (DFO) carried out a large number of aerial and boat surveys, that, once combined, covered all eastern Canadian waters. Here we present several spatial analyses of this database with a focus on the St. Lawrence Estuary. Seasonal occurrence of blue, fin, humpback, and minke whale is first presented as monthly maps of all observations. Then, in order to better illustrate the general pattern of the species sightings, a kernel analysis was used to represent the spatial distribution as well as the relative densities of monthly observations from two systemic survey programs: 1) an intensive boat survey program conducted in the northern part of the St. Lawrence Lower Estuary and 2) an aerial survey program used to assess population size of the St. Lawrence Estuary beluga. Finally, a modelling approach using the relationships between the occurrence of these four whale species and several variables characterizing the marine environment was used to map potentially important zones to be considered when defining management areas aiming to avoid risk of vessel strikes. We discussed the advantage and caveats of the different representations of the observations data.

MATERIAL AND METHODS

OBSERVATION DATABASE

The observations from 72 aerial surveys and 137 boat surveys were used (Table 1). Most of the surveys covered the St. Lawrence Estuary (64 aerial surveys, 130 boat surveys), some covered the Gulf (26 aerials surveys and 25 boat surveys) and only two large-scale surveys covered a continuous area from the Estuary and Gulf of St. Lawrence, to the continental shelves from Northern Labrador to southern Scotian Shelf. The Bay of Fundy was covered only once by a large scale survey (Figure 1 and Figure 2).

While this dataset encompasses surveys conducted with various platforms from 1995 to 2017, the same information was recorded. It includes weather conditions (sea state, glare intensity, cloud cover), and for each marine mammal sighting, information allowing calculation of its location (inclination angle using a clinometer (Suunto), or reticles in binoculars, angle from the platform heading and finally altitude, speed and location of the platform obtained from a GPS device) (e.g. Gosselin et al. 2017, Lacroix-Lepage 2018).

AREA SURVEYED AND EFFORT MAPS

The area surveyed was represented by the field of view of the observers when they were on effort. The field of view was considered as a buffer around the platform track with a width (3000 m) equal to the 95th percentile of the perpendicular distances between the platform track and the observations of the four species considered (i.e. blue, fin, humpback and minke whale). Potential differences in the "on effort" period between the left and the right sides of the platform was taken into account with independent right and/or left side buffers. Differences between platform are taken into account in a later step of the analysis (see sub-section "Modeling and weighting information").

To present observations of each species in a more efficient way, effort maps were linked to each of the monthly occurrence maps. By doing so, it avoids false interpretations when, for example, no observation was mentioned in a zone but this zone was in fact not covered by the surveys, or conversely, when many observations were recorded in an area where effort was substantially higher than elsewhere. The monthly effort maps were calculated on a grid of 1000 x 1000 m cells covering the St. Lawrence Estuary. Cell values were calculated as the sum of the surveyed areas covering each cell.

SYSTEMATIC SURVEYS AND KERNEL ANALYSIS

Two series of 110 boat surveys and 49 plane surveys, respectively, were conducted in the St. Lawrence Estuary following a systemic survey design. Boat surveys (referred later on as the "Cetus survey", a 10 m boat with a platform 2.1 m above water level) were conducted on a weekly basis (weather permitting) between 2009 and 2015, generally from May to October (except April-November 2010, and May-November in 2015) and covered the northern portion of the Lower Estuary between Tadoussac and Forestville (Figure 21). Visual aerial surveys were conducted using small aircraft (Cessna 337 or Partenavia P68 Observer) flying at target altitude of 305 m to assess population size and distribution of St. Lawrence Estuary beluga. They covered their entire summer distribution area including both the Upper and Lower Estuary from Petite-Rivière-Saint-François (15 km upstream of Baie St Paul) to Rimouski. Six of them also extended east of Rimouski and covered the downstream portion of the Lower Estuary. These surveys were conducted from mid-July to early September between 2001 and 2017 (1 in 2001, 5 in 2003, 14 in 2005, 3 in 2007, 2 in 2008, 9 in 2009, 10 in 2014, 2 in 2015, 3 in 2016; Gosselin et al. 2001, 2007, 2014, 2017, Lawson and Gosselin 2009). Boat and plane surveys were systematic with random placement of parallel transect lines separated by 4.5 and 4 nautical miles respectively and oriented perpendicularly to the main axis of the Estuary.

The fixed kernel method (Worton 1989) was used to represent monthly densities of observations for the four whale species. The kernel method is sensitive to the bandwidth (*h*, Figure 3) controlling the spatial influence range of each observation. To make the kernel maps comparable within a series of aerial or boat surveys, we used a fixed bandwidth selected to account for line spacing, so to limit the influence of information obtained on a given transect to the space between the neighbouring transects (Figure 3). Kernel maps were created for each survey date using a grid of 500 x 500 m cells covering the Estuary. For each survey type (aerial or boat based), kernel maps from surveys conducted in the same month were merged together by calculating mean kernel densities for each grid cell. For aerial surveys, two regions were considered separately for the calculations as survey effort greatly differ (49 surveys covering the Upper Estuary and the upper portion of the Lower Estuary vs 6 covering the lower portion of the Lower Estuary). In addition to monthly maps, composite maps were calculated for periods with the highest coverage (i.e. May to October for the Cetus survey and mid-July to mid-September for the plane surveys). For comparative purposes, a composite map was produced for the Cetus surveys to match the period of aerial surveys (mid-July to mid-September).

SPECIES DISTRIBUTION MODELLING

Data selection

To increase sample size, species distribution models of blue, fin and humpback whales were fitted to data from surveys conducted in both the Estuary and the Gulf, and therefore models represent their habitat selection on a larger spatial scale comparable to the scale of documented movements of these species in the St. Lawrence (Ramp et al. 2015, Lesage et al. 2017). For the minke whales, only surveys conducted into the estuary were considered. Only surveys with at least one observation of the species of interest were used in the modelling exercise.

Extracting environmental data

The environment used by whales was described by extracting for each sighting, location and time specific information on water depth, bottom slope, sea surface temperature (SST), distances from specific isobaths, distance to of thermal fronts and their frequency of occurrence. Depth was obtained from a 100 m resolution raster map created by interpolating data from the Canadian Hydrographic Service. Bottom slope was derived from the depth map by calculating the maximum rate of depth change (in degrees) between neighboring cells. Prior to September 2010, SST data was extracted from NOAA's Advanced Very High Resolution Radiometer (AVHRR) satellite images (≈1.1 km resolution). From 2011 onward, SST data was extracted from maps generated by the Group for High resolution Sea Surface Temperature (GHRSST) by combining complementary satellite and in situ observations within Optimal Interpolation systems. Mean SST values over the last 3, 7, and 15 days including observation date were considered. Daily SST images were not used as they did not always offer a complete coverage of the study area and therefore the 3-day mean maps centered on each observation date were considered representative of the SST on the observation date. The 3-day mean maps were also considered with a 3, 7, and 15 days lag from the observation date to examine potential delayed responses to thermal conditions. Thermal fronts were identified on daily SST maps with the Cayula and Cornillon edge detection algorithm (Cayula and Cornillon 1995) available in the Marine Geospatial Ecology Tools (MGET) toolbox developed for ArcGIS 10 (Roberts et al. 2010). Distance to the closest front was calculated as well as the frequency of occurrence of thermal front in an area of 1 km around each observation. Finally, distances relative to the 20m and 200m isobaths were considered as they were found representative of the location of steeper bottom slopes between the coastal waters and the shelf , and between the shelf and the Laurentian Channel, respectively.

Although information on chlorophyll a was available for the study area, it was not included due to the confounded effect of coloured dissolved organic matter in the Estuary when calculating chlorophyll a values from satellite imagery resulting in severe overestimations (Laliberté et al. 2018).

While recognising it is not possible to fully describe the environment "not used" by the whales, due to availability and detection biases (Buckland et al. 2004), we tried to avoid including conditions where potential whale occurrence was high (see also next section). Random points were drawn from the surveyed area with a density of 2 point/km², however, no random point was allowed in an area of 1km around each sighting. Each random point was given a time stamp corresponding to the date and time at which the distance from the survey platform was the shortest. We also associated the local conditions (sea state, glare intensity, cloud cover) prevailing during the survey at that date and time. Finally, the same variables describing the environment of each whale sighting (i.e. Depth, Slope, SST, thermal fronts) were also extracted for those random points.

Modelling and weighting information

Relationships between whale occurrences and environmental variables were assessed using logistic regressions fitted as Generalized Additive Mixed Models (GAMM) using the function "BAM" (special version of the "GAM" function for large dataset) from the R package "mgcv" (Wood et al. 2015, Wood et al. 2017). To constrain the model to compare environmental conditions within each survey (i.e. not mixing conditions between the various surveys), the date was considered as a random effect in the models (see "random.effects" in the help pages of the "mgcv" package). Only one variant of each variable (depth, slope, SST, distance to specific isobaths, distance to the closest thermal front, frequency of thermal front occurrence) was introduced in the full models. No interactions were tested. Multicollinearity was estimated by calculating the variance inflation factor (VIF) using the R package "usdm" (Naimi 2017). Variables with a VIF > 10 were not considered in the models. To account for potential spatial autocorrelation the latitude-longitude interaction term was also added to the models (Wood 2006). Smoothed terms were represented using penalized regression splines with smoothing parameters selected by Maximum Likelihood (ML). To keep the ecological interpretability of functional relationships, we limited each spline to 4 degrees of freedom.

Even if we avoided sampling random points in the vicinity of the sightings, one could still argue that random points representing pseudo-absences could still be located where an animal is present but not detected. To minimize this problem, we weighted the data included for each random point by an index of detectability. We first used the "ddf" function from the R package "Distance" (Miller et al. 2019) to obtain detection curves accounting for perpendicular distance of the sighting, platform type (i.e. small size research vessel, medium size research vessel, large size research vessel, small size plane, medium size plane) and local conditions during the survey (sea state, glare intensity). We tested both conventional distance sampling (CDS) and multiple-covariate distance sampling (MCDS) formulations with hazard-rate and half normal key functions. For each of the four species, the best detection model was selected as the one with the lower Akaike Index Criterion (AIC) value and a meaningful output (e.g. models predicting better detection with increasing glare or sea state were discarded). To be detected, an animal also had to be available for detection (i.e. not completely hidden from the observer). For marine mammals, availability is related to the proportion of time animals spend near the surface and diving. In line-transect surveys, we also have to consider the speed of the survey platform and the time the location of an animal remains in the field of view of an observer (Forcada et al. 2004 and Gomez de Segura et al. 2006). The final index of detectability (varying between 0 and 1) is obtained from the product of probability of detection and availability. Using this value as a weighting index in the GAMM controlled for the characteristics of each survey conditions and the decreasing detectability with distance from survey platform. Thus, a random point located near the platform will have a higher weight than a random point located farther away. Another way to present this is to consider that if a random point is near the platform, the probability of detection is high and therefore if nothing was detected at this point, the probability that this random point is a "true" absence is also higher than farther away. As a complement, sightings were given a weight of 1 because they represent true presence.

Model selection and performance testing

Models were fitted to a random selection of 80% the observations and 80% of the random points. Model selection was made using the shrinkage approach (Marra and Wood 2011). This method allows the exclusion of a covariate not bringing any information into the model by reducing the effective degree of freedom of its smooth term to 0, or near 0. When such a situation occurred, the variable was removed and the model refitted. The final model was tested using the remaining 20% of the dataset. This procedure was repeated 10 times for each of the species models. If the best model selected in each of the 10 iterations differed, the frequency of occurrence of each covariate was examined and the final model for a species was based on the variables occurring in at least 70% of models.

Model performance was evaluated with different methods. A receiver operating characteristic (ROC) curve (Fielding and Bell 1997) was constructed both for the training set (i.e. comparing predictions with the data used to fit the model) and the testing set (this time comparing predictions with an independent dataset. i.e. the 20% not used to fit the model). The area under the ROC curve (AUC) was then used as a threshold-independent measure for model performance (Manel et al. 2001). The AUC ranges from 0.5 for models with no discriminatory power, to 1 for models with perfect discrimination. Intermediate values were interpreted as follows: 0.5-0.6 = fail, 0.6-0.7 = poor, 0.7-0.8 = fair, 0.8-0.9 = good, 0.9 to 1 = excellent. The Youden index (Youden 1950) was used to define the optimal threshold for classifying model predictions into presence or absence and construct a confusion matrix allowing to obtain the proportion of correct classifications. Finally, the True Skill Statistic (TSS; Allouche et al. 2006), and the Symmetric Extremal Dependence Index (SEDI; Ferro and Stephenson 2011; Wunderlich et al. 2019), two other measure of model goodness, were also calculated. They both range from -1 to +1 with +1 indicating perfect agreement, and values of zero or less suggesting a performance no better than random. Finally, spatial representations of the final model predictions for each species were produced and compared visually to observations.

RESULTS

MONTHLY MAPS OF OBSERVATIONS IN THE ST. LAWRENCE ESTUARY

One hundred and ninety four DFO surveys were conducted in the St. Lawrence Estuary including 130 boat and 64 plane surveys. Boat surveys covered April to December with most of the surveys (96.2%) conducted between May and October. Plane surveys were mostly (78.4%) conducted between July and September with only a few of them in February, March, May, November and December (Figure 4).

Minke whales were detected in the St. Lawrence Estuary from April through November (See Appendix 1). The spatial distribution of the observations before the month of August was mainly limited to the lower estuary, *i.e.* downstream of the confluence with the Saguenay River, and seems to be expanding ~25 km upstream in August and September, however this may reflect the temporal variation of the observation effort. From May to October (i.e. the time frame with the best survey coverage), a large number of the observations (72% of the 989 sightings) occurred in the northern part of the estuary in shallow waters between Cap Colombier (20 km downstream of Forestville) and Tadoussac and at the head of the Laurentian channel. Again, this also corresponds to the area where the largest amount of effort occurred (Figure 5). Minke whales could also be found in a polygon delimited by Tadoussac to Saint-Siméon on the north shore and by Cacouna to Trois-Pistoles on the south shore. Only a few observations were recorded upstream and were located mainly on the north shore between Saint-Siméon and Cap-aux-Oies (20 km upstream of La Malbaie). Downstream from Betsiamite on the North shore and Trois-Pistoles on the south shore, minke whales also occurred in shallow waters but the density of observation was lower as was the observation effort.

Fin whale observations were recorded from May through November. Their spatial distribution did not seem to change a lot over that period (Appendix 2). More than half of the fin whale sightings (57% of 259 sightings) occurred at the head of the Laurentian channel, the rest were spread along the Laurentian channel with a density that seems to decrease downstream (Figure

10). However, the observation effort is also greatly lower downstream of Forestville-Rimouski. No fin whales were sighted upstream of Saint-Siméon – Rivière-du-Loup.

Humpback whales were sighted from May through October (Appendix 3). They were mainly located at the head of the Laurentian (69% of the 139 sightings; Figure 15) with no observations upstream of this area. Downstream, their distribution followed the Laurentian channel with a little area of higher density of observations in August off "Pointe à Boisvert" located 20 km upstream of Forestville.

Blue whales were observed from March through November (Appendix 4). Seen downstream of Les Escoumins from April to June, their spatial distribution extends to the head of the Laurentian channel afterwards. Contrary to the other three species, there is only a few Blue whale sightings at the head of the Laurentian channel (8% of 263 sightings from May to October; Figure 20). The area with the highest density of observation also corresponds to the sector with the highest observation effort. Sightings generally occurred in the deeper part of the Laurentian channel, but sometimes in shallower areas off Forestville. No observations of blue whale were recorded upstream of Tadoussac.

KERNEL MAPS OF SYSTEMATIC SURVEYS

Kernel analysis of the observations obtained with the Cetus survey program showed that areas where minke whales concentrate remain the same over the different months (Appendix 5). The highest densities of observations were clearly associated with bathymetry, in particular the 20 m isobaths (*i.e.* area of steeper bottom slopes between coastal waters and the shelf) on the north shore and form a U shape around the head of the Laurentian channel (Figure 7). Locations of fin whale concentration areas from one month to the next are less clear due to the lower number of sightings (Appendix 6). As shown on the composite map comprising observations from May to October, the head of the Laurentian channel repeatedly includes areas of high densities (Figure 11). While the number of sightings was even lower for humpback whales, the result is much more obvious. Kernels confirm the importance of the head of the Laurentian channel (Appendix 7) and the composite map suggests that a sector located on its northernmost part is highly used (Figure 16). Finally, kernels based on the Cetus surveys suggest that blue whale concentrate between Les Escoumins and Forestville, with a preference for the area around the northern slope of the Laurentian channel (Appendix 8 and Figure 21).

The larger spatial coverage of the aerial surveys gave a slightly different image of minke whale distribution. While shallow waters on the north shore of the lower estuary, covered by the Cetus survey, were also identified as important, the higher densities of observations were located in a polygon delimited by Tadoussac to Saint-Siméon on the north shore and Cacouna to Trois-Pistoles on the south shore (Figure 7 and Appendix 13 and 14). Moreover, kernels showed that minke whale observations generally did not occur in waters less than 20 m deep but can be found in waters from 20 to 100 deep on the north and south shore with some concentrations of observations near Forestville, Baie-Comeau and about 20 km east of Matane. Fin whale kernels showed an area of high density of observations close to the north shore just off Les Escoumins in July and revealed a high occurrence of observations at the head of the Laurentian channel in August, particularly on its southeastern section (Figure 11 and Appendix 15). As shown with the Cetus survey data, kernels based on aerial surveys' observations confirm that an area located on northern part of the head of the Laurentian Channel is highly used by humpback whales particularly in August (Figure 17 and Appendix 16). Spatial distribution of blue whale sightings were spread over the Laurentian channel (Figure 22 and Appendix 17 and 18) with higher densities located off Pointe-aux-Outardes (20 km east of Betsiamites on the north shore), Forestville, and Les Escoumins. However, concentrations located near Les Escoumins were closer to the coast (< 3km).

SPECIES DISTRIBUTION MODELS

Successive modelling iterations using training/testing sets based on the minke whale data ended in 9 out of 10 cases with the same set of variables in the model including bathymetry, slope and distance to the 20 m isobaths. The latter also occur in the 10th iteration model which, in addition, also considers the influence of the distance to the closest thermal front (Table 2). The final model considering bathymetry, slope and distance to the 20 m isobaths indicated that minke whales were more likely to be observed in shallower waters and steeper slopes (>20 degrees) with an even higher probability when it comes close to the 20 m isobaths (*i.e.* area of steeper bottom slope between coastal waters and shelf; Figure 8).

The three larger whales (i.e. fin, humpback and blue whales; see data selection section), models were based on data coming from the Gulf and the Estuary and therefore represent larger scale habitat selection.

For fin whales, models suggested a relationship with the bathymetry (8 out of 10 iterations) and the distance to the 200 m isobath (7 out of 10 iterations). Other covariates occurred less than 40% of the time in the models (Table 2). Considering only conditions observed in the Estuary, the final model including bathymetry and the distance to the 200 m isobath indicating that fin whales were more likely to be observed where the bathymetry is between 60 and 270 m depth (Figure 13 a). The model also suggests that the probability of observation increases with the proximity to the 200 m isobaths (*i.e.* area of steeper bottom slope between the shelf and Laurentian Channel; Figure 13 b).

Humpback whale models always included the influence of the bottom slope and generally also considered the distance from the 200 m isobath (8 over 10 iterations; Table 2). The final model considering these variables suggests that humpback whales are more likely observed close the 200 m isobaths in areas where the bottom slope is >20 degrees (Figure 18).

The blue whale models are the only ones that included a dynamic variable (i.e. Thermal front frequency 1 km around the location) in all iterations (Table 2). Bathymetry was the other variable always present. Other covariates occurred in less than 50% of the iterations. The final model indicated that blue whales were more likely observed in water deeper than 115 m (Figure 23a). This probability increased until 215 m then decreased as the depth increased. The inclusion of the effect of the thermal front frequency in the model did not change the relationship with the depth, but suggested an avoidance of frontal areas by blue whales (Figure 23b and c).

Measures of Area Under the Curve (AUC) generally suggested that predictions obtained from models produced for minke, humpback and blue whales were good (i.e. mean AUC 0.927, 0.827, and 0.869 respectively) when compared to their respective testing datasets (Table 2). The models for fin whales were at most considered good but for the majority were only considered as fair (mean AUC = 0.726). Models for minke and blue whales were the most efficient in identifying correctly presence (mean of 84 and 80% respectively;Table 2) and absence (mean 70 and 79% respectively). Fin whale and humpback models were less successful in predicting presence (mean 51 and 67% respectively) but were correctly identifying the absences (mean 78 and 83% respectively). The TSS does not consider that fin whale models were less efficient than the models for the other species, but the SEDI clearly did (mean 0.7, 0.75, 0.66 for minke, blue and humpback models respectively and 0.41 for fin whale models).

The spatial representation of model predictions for each species (Figure 9, Figure 14, Figure 19, Figure 24) showed a good correspondence with the observations (Figure 5, Figure 10,Figure 15,Figure 20). For minke whale, the predictions of the model highlight the areas of high densities of observations revealed by the kernel analysis (Figure 6 and Figure 7). The fin whale prediction map correctly represents the distribution of the observations at the head of the Laurentian channel (Figure 14 vs Figure 10), but suggests a high probability of fin whale occurrence on the southern slope of the channel that was not revealed by the observations recorded in our database. Note that the intensive Cetus survey program did not cover this area. Predictions of the humpback model are less clear (Figure 19). While the model correctly suggested a high probability of occurrence at the head of the Laurentian channel where most of the observations were recorded, it also indicates a rather high probability of occurrence extending 15 km upstream where no observations occurred (Figure 15). Finally, the blue whale model has a good fit with the observations in the area between Tadoussac and Betsiamites (Figure 24 vs Figure 20) identifying also the shallower area off Forestville with a relatively high probability of occurrence. But, just as the fin whale model, it suggests a high probability of occurrence on the southern slope of the Laurentian channel where only a few observations were recorded.

DISCUSSION

Long term management and recovery of baleen whales rely on our knowledge about their distribution and our capacity to protect important habitats. Such information is limited in the St. Lawrence Estuary, an area where minke, humpback, fin and blue whales are exposed to a high level of maritime traffic and are potentially at risk of vessel strike. Using observations collected during more than 20 years of aerial and boat surveys conducted by DFO, we propose several means to present the information on seasonal occurrence and spatial distribution of those four species, along with the limitations linked to each of them.

Spatial representation of raw observation data constitutes the first tool generally used to consider this information. However, in most cases, such data are presented without considering the observation effort which can lead to incorrect conclusions (Ruete 2015). This includes stating that a species is absent from an area because no observations were recorded while in fact the area considered was not covered by any survey or only a small number of them. Or in the opposite way concluding that the density of the species was high because numerous observations were recorded, but with an observation effort much higher than in other areas. To avoid these problems, data presented in this document are always linked to the corresponding effort map. However, this process does not constitute an easy solution for managers. A simple combination of the raw observation data with effort maps in the form of gridded densities of sightings is possible but with the caveat that estimated density values can change with grid cell size and the position of the grid used to make the calculations (Silverman 1986). Therefore, this information was not presented here.

The second approach considered in this document involves the use of the kernel method to illustrate the observation data. Contrary to the presentation of raw data, kernel maps created in this study are the product of the recurrence and the number of observations in an area over the surveys. This kind of analysis allowed for synthesis of the observation information and extraction of the global pattern occurring in the data, facilitating its interpretation (e.g. Figure 9). Moreover, the result is not influenced by effects of grid size and placement. However, such a method has some prerequisites. First, the kernel analyses are dependent on a smoothing factor that we fixed based on the design of the surveys to ensure comparability among surveys (see Materials and Methods). Various optimisation methods exist to define this value (Silverman 1986, Jones et al. 1996, Horne and Garton 2006), and other considerations than the survey design could have been included. Thus, for example, the area of influence defined by the smoothing factor could have been chosen to represent the area around each observation that we consider as important to protect (e.g. distance requirements for boat proximity). Our choice of smoothing factor combined with the low number of sightings available for humpback, fin or blue whales when data is split by month, has sometimes resulted in maps showing only the location of each sighting, surrounded with small area of decreasing density (Appendices 6, 7, and 8). Using a larger area of influence (i.e. larger smoothing factor) would have provided a more continuous representation of the distribution that may however give a false impression of representativeness despite the low number of observations. Another prerequisite of kernel analysis is that it should be applied on an area where the survey effort is equal on the whole surface. We used only systematic surveys to ensure the most regular effort over the study area and we applied it on areas that have most of its surface with a nearly identical effort, but some part were covered with a lower effort which has to be taken into account when interpreting the results. Due to these limitations, only part of the data available can be used leading to a loss of information. Finally, kernel-based maps obtained here illustrate “only” the distribution of the observations and not the habitat used by the species. Including environmental characteristics requires more complex analysis such as the one we used with our modelling approach.

The species distribution modelling approach was the most advanced and complete analysis used in this study. The methodology allowed us to include all of the survey observation data whether they were conducted with a systematic design or not. It also integrates the characteristics of the species observed, a description of the environment used and the survey conditions when sightings occurred. The result is a synthesis of all this information in the form of a single map showing relative probability of occurrence for each species covering the whole Estuary. As in every modelling exercise, the quality of the result depends on the quality and the quantity of the data considered as input. Areas of high probability of occurrence of the four whale species have been identified in the St. Lawrence Estuary using the data collected from systematic surveys and from platforms of opportunity (i.e. during other research activities) over more than 20 years. Synthesizing the information recorded mainly from May to October, the model-based maps produced can be seen as an informed spatial interpolation valid for this time period.

This work, along with a complementary study involving observations data collected in the Saguenay St. Lawrence Marine Park (Martins et al. In press), represent important contributions on spatial and temporal distribution of blue, fin, humpback and minke whales in the St. Lawrence estuary. Despite the fact that most of the survey effort was concentrated between May and October, 5 boat surveys and 11 plane surveys conducted outside of this period allowed to assess the presence/absence of each species from February to December. However, the variability in effort coverage and intensity among the months preclude a clear analysis of the seasonal evolution of the species distribution. We believe that the period with the higher survey effort cover nonetheless most of the period when these four species are present in the Estuary. Humpback whales are known to reproduce in winter in the Caribbean Islands (Whitehead and Moore 1982) and therefore reproductive individuals are likely to be outside of the St. Lawrence in winter. The exact location of reproduction is not known for the other species, but seasonal movements from blue whales tagged in the St. Lawrence estuary in summer show seasonal movement out the Estuary and the Gulf in late autumn (Lesage et al. 2017, DFO 2018) and North Atlantic fin whale and minke whale have been shown to start a southward migration in that season (Mitchell 1974, Sergeant 1977, Risch et al. 2014). Ice cover is important in the Estuary in winter and believed to limit access for most large whales, but blue whales and fin whales have been detected in the Estuary and the Gulf during the winter months (Simard et al. 2016, Roy et al. 2018) and ice entrapment has been documented in the South East Gulf (Stenson et al. 2003, Moors-Murphy et al. 2019).

While the presentation of raw observation and kernel analysis provide some value in illustrating realised habitat use, the modelling approach used here allowed mapping of both the realised and the potential habitat use by integrating all the data available and correcting, to some extent, the differences in survey effort over the area of interest. Generally considered as a hot spot of biodiversity due to the active mixing and marine mammal biodiversity (Simard 2009, Cotte and Simard 2015), the area of the head of the Laurentian channel was clearly identified by our models as an important habitat for fin, humpback, and minke whales. This is also one of the main conclusions of Martins et al. (In press) based on data collected from systematic surveys and whale watching activities monitoring conducted in this area of the St Lawrence estuary. In accordance with Doniol-Valcroze et al. (2012) and Ramp and Sears (2013), our models predicted a high probability of blue whale occurrence in the Laurentian channel and its slopes between Les Escoumins and Forestville where krill species *Thysanoessa spp.* and *Meganyctiphanes norvegica,* recognized as important in the diet of this whale species (Gavrilchuk et al. 2014), were found in high densities (McQuinn et al. 2016). The slopes of the Laurentian channel, particularly upstream of Forestville are also highlighted for the two other larger species. Finally, slopes in the shallower waters encompassing the 20 to 100 m isobaths were also identified as areas of high probability of occurrence for minke whales. The model-based maps presented here likely cover the seasons of higher presence of these four species in the Estuary and could thus be used to delineate areas with a potentially high risk of collision with vessels. They should therefore be taken into account when defining management plans aiming to protect these four species of baleen whales in the St. Lawrence Estuary.

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TABLES

Table 1. Summary description of surveys included in the observation database considered in the analyses. Kernel analysis were realized only on systematic surveys using the same protocol over the same area (i.e. Multispecies boat surveys referred as Cetus surveys and plane surveys used to assess the size and distribution of the beluga population also including part of two large surveys TNASS and NAISS covering the area). Blue, fin and humpback whale occurrence models were based on the whole dataset, while minke whale models used only surveys covering the estuary.

Survey name	Survey type	Nb of surveys	Platform	Spatial coverage		Temporal coverage	Effort
				Estuary	Gulf		
Multispecies boat surveys (Cetus surveys)	Systematic	110	Boat	X		May - Oct. 2009 - 2015	1 survey / week, weather permitting
Observers on multidisciplinary missions	Non systematic	18	Boat	X (13)	X(18)	Aug. 1995 - 1998; Dec. 2001; May - June - Nov. 2002; Aug. 2005; Aug. 2014; June - Aug. - Sept 2015; Aug. - Sept. 2016; June - Aug. - Sept. 2017	1 survey / month
Observers on acoustic missions	Non systematic	9	Boat	X(7)	X(7)	Aug. 2009; Aug. 2011; June 2012; Aug. 2012; July - Aug. 2013; May 2014; June 2015	1 survey / month
Beluga population assessment surveys	Systematic	45	Plane	X		July - early September 2001; 2003-2005;2007-2009;2012-2014	1 to 14 surveys / year
Seasonal distribution beluga surveys	Systematic	19	Plane	X (12)	X (18)	Spring 2013 - 2015; Fall 2012 - 2014; Winter 2013 - 2015	1 to 2 surveys / season
Other beluga surveys	Systematic	4	Plane	X (4)	X (3)	September 2002; March 2004	1 survey / month
Multispecies aerial surveys (TNASS, NAISS*)	Systematic	4	Plane	X	X	July - August 2007; August 2016	1 survey / month

* TNASS and NAISS are stated for Trans North Atlantic Sightings Surveys and North Atlantic International Sightings Surveys respectively

Table 2. Models selected in each iteration of training/testing sets and evaluation statistics (i.e. Proportion of deviance explained, Area Under the Curve when predictions are done on the dataset used to fit the model (AUC Training) or on the testing dataset (AUC Testing), proportion of correct classification for presences (Classif 1vs1) or absences (Classif 0vs0), mean correct classification, True Skill Statistics (TSS), Symmetric Extremal Dependence Index (SEDI)).

Species	Model	% Deviance Explained	AUC Training	AUC Testing	% Classif 1vs1	% Classif 0vs0	Mean correct classif	TSS	SEDI
Minke whale	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	38.2	0.925	0.884	91.3	70.4	80.9	0.686	0.785
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39.2	0.929	0.841	80.0	74.7	77.3	0.698	0.706
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39.8	0.930	0.825	76.0	73.0	74.8	0.711	0.651
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39	0.927	0.867	87.0	68.0	77.9	0.689	0.724
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39.1	0.928	0.844	83.3	66.0	74.7	0.7	0.655
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39.2	0.927	0.865	87.3	66.3	76.8	0.689	0.704
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	39.2	0.929	0.851	82.7	70.3	76.5	0.7	0.691
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	38.6	0.926	0.871	88.7	64.7	76.7	0.697	0.706
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	38.9	0.927	0.85	82.0	70.5	76.2	0.687	0.686
	s(Distance Thermal Front) + s(Bathymetry) + s(Bottom slope) + s(Distance Iso 20m)	38.5	0.924	0.852	79.3	74.2	76.8	0.692	0.693
	Mean	38.97	0.927	0.855	83.8	69.8	76.9	0.6949	0.7001
	CI 95% inf	38.7	0.926	0.844	80.8	67.6	75.8	0.690	0.677
	CI 95% sup	39.2	0.928	0.866	86.7	72.0	77.9	0.700	0.723
Fin whale	s(Bathymetry) + s(Bottom slope)	29.2	0.934	0.711	45.5	77.0	61.3	0.738	0.33
	s(Bathymetry) + s(Distance Iso 200m)	29.6	0.935	0.717	50.5	79.0	64.8	0.74	0.423
	s(Bathymetry) + s(Distance Iso 20m)	29.5	0.938	0.696	38.6	81.4	60.0	0.749	0.304
	s(Bottom slope) + s(Distance Iso 200m)	28.8	0.932	0.73	58.4	70.7	64.6	0.741	0.409
	s(Bathymetry) + s(Distance Iso 20m)	30	0.937	0.695	35.6	79.5	57.6	0.751	0.232
	s(Bathymetry) + s(Bottom slope) + s(Distance Iso 200m)	28.3	0.930	0.754	52.5	81.4	67.0	0.729	0.481
	s(Bottom slope) + s(Distance Iso 200m)	29.4	0.936	0.717	56.4	75.6	66.0	0.75	0.45
	s(SST day) + s(Bathymetry) + s(Distance Iso 200m)	30.2	0.936	0.747	52.5	82.0	67.2	0.738	0.489
	s(SST day) + s(Bathymetry) + s(Distance Iso 200m)	30	0.933	0.749	63.4	73.8	68.6	0.741	0.51
	s(SST day) + s(Bathymetry) + s(Distance Iso 200m)	29.1	0.929	0.75	57.4	78.3	67.9	0.726	0.498
	Mean	29.41	0.934	0.7266	51.1	77.9	64.5	0.7403	0.4126
	CI 95% inf	29.0	0.932	0.713	45.6	75.6	62.2	0.735	0.354
	CI 95% sup	29.8	0.936	0.741	56.6	80.1	66.8	0.745	0.471
Humpback whale	s(Bottom slope) + s(Distance Iso 200m)	29	0.931	0.796	62.3	86.3	74.3	0.725	0.654
	s(SST last 3 days) + s(Bottom slope) + s(Distance Iso 200m)	28.8	0.927	0.807	65.2	81.4	73.3	0.716	0.625
	s(Bottom slope) + s(Distance Iso 200m)	28.6	0.928	0.841	66.7	84.8	75.8	0.721	0.679
	s(Front Freq Mean 1km) + s(Bathymetry) + s(Bottom slope) + s(Distance Iso 200m)	28.7	0.929	0.837	75.4	78.9	77.1	0.717	0.701
	s(Front Freq Mean 1km) + s(Bathymetry) + s(Bottom slope)	28.9	0.928	0.838	72.5	77.4	74.9	0.719	0.655
	s(Front Freq Max 1km) + s(Bottom slope) + s(Distance Iso 200m)	28.5	0.929	0.849	68.1	85.3	76.7	0.724	0.699
	s(SST lag 3d) + s(Bathymetry) + s(Bottom slope)	29.7	0.932	0.845	71.0	82.6	76.8	0.729	0.697
	s(Bottom slope) + s(Distance Iso 200m)	29.7	0.937	0.799	71.0	78.1	74.6	0.737	0.648
	s(Front Freq Mean 1km) + s(Bathymetry) + s(Bottom slope) + s(Distance Iso 200m)	30.7	0.936	0.808	62.3	83.1	72.7	0.744	0.615

Species	Model	% Deviance Explained	AUC Training	AUC Testing	% Classif 1vs1	% Classif 0vs0	Mean correct classif	TSS	SEDI
	s(Front Freq Max 1km) + s(Bathymetry) + s(Bottom slope) + s(Distance Iso 200m)	30	0.932	0.854	59.4	88.5	74.0	0.722	0.653
	Mean	29.26	0.931	0.8274	67.4	82.6	75.0	0.7254	0.6626
	CI 95% inf	28.8	0.929	0.814	64.2	80.3	74.1	0.720	0.644
	CI 95% sup	29.7	0.933	0.841	70.6	84.9	76.0	0.731	0.681
Blue whale	s(SST lag 15d) + s(Front Freq Mean 1km) + s(Bathymetry) + s(Distance Iso 200m)	29.4	0.936	0.882	85.3	77.4	81.3	0.728	0.783
	s(Front Freq Mean 1km) + s(Bathymetry)	29.2	0.938	0.881	77.9	81.9	79.9	0.726	0.755
	s(SST last 3 days) + s(Front Freq Mean 1km) + s(Bathymetry) + s(Distance Iso 200m)	27.7	0.933	0.873	83.8	78.4	81.1	0.725	0.777
	s(Front Freq Mean 1km) + s(Bathymetry)	29.4	0.942	0.881	85.3	81.3	83.3	0.75	0.815
	s(SST lag 15d) + s(Front Freq Mean 1km) + s(Bathymetry) + s(Distance Iso 200m)	30.2	0.941	0.88	80.9	81.5	81.2	0.725	0.778
	s(Front Freq Mean 1km) + s(Bathymetry)	29.2	0.939	0.851	70.6	78.3	74.4	0.733	0.645
	s(Front Freq Mean 1km) + s(Bathymetry) + s(Distance Iso 200m)	29.5	0.937	0.877	85.3	78.0	81.6	0.721	0.788
	s(SST last 3 days) + s(Front Freq Mean 1km) + s(Bathymetry) + s(Distance Iso 200m)	29.4	0.937	0.831	69.1	76.9	73.0	0.723	0.614
	s(Front Freq Mean 1km) + s(Bathymetry)	28.9	0.938	0.866	80.9	76.2	78.5	0.732	0.729
	s(Front Freq Mean 1km) + s(Bathymetry)	30.1	0.942	0.868	80.9	80.9	80.9	0.751	0.773
	Mean	29.3	0.938	0.869	80.0	79.1	79.5	0.7314	0.7457
	CI 95% inf	28.9	0.937	0.859	76.3	77.8	77.5	0.725	0.705
	CI 95% sup	29.7	0.940	0.879	83.7	80.4	81.6	0.738	0.786

FIGURES

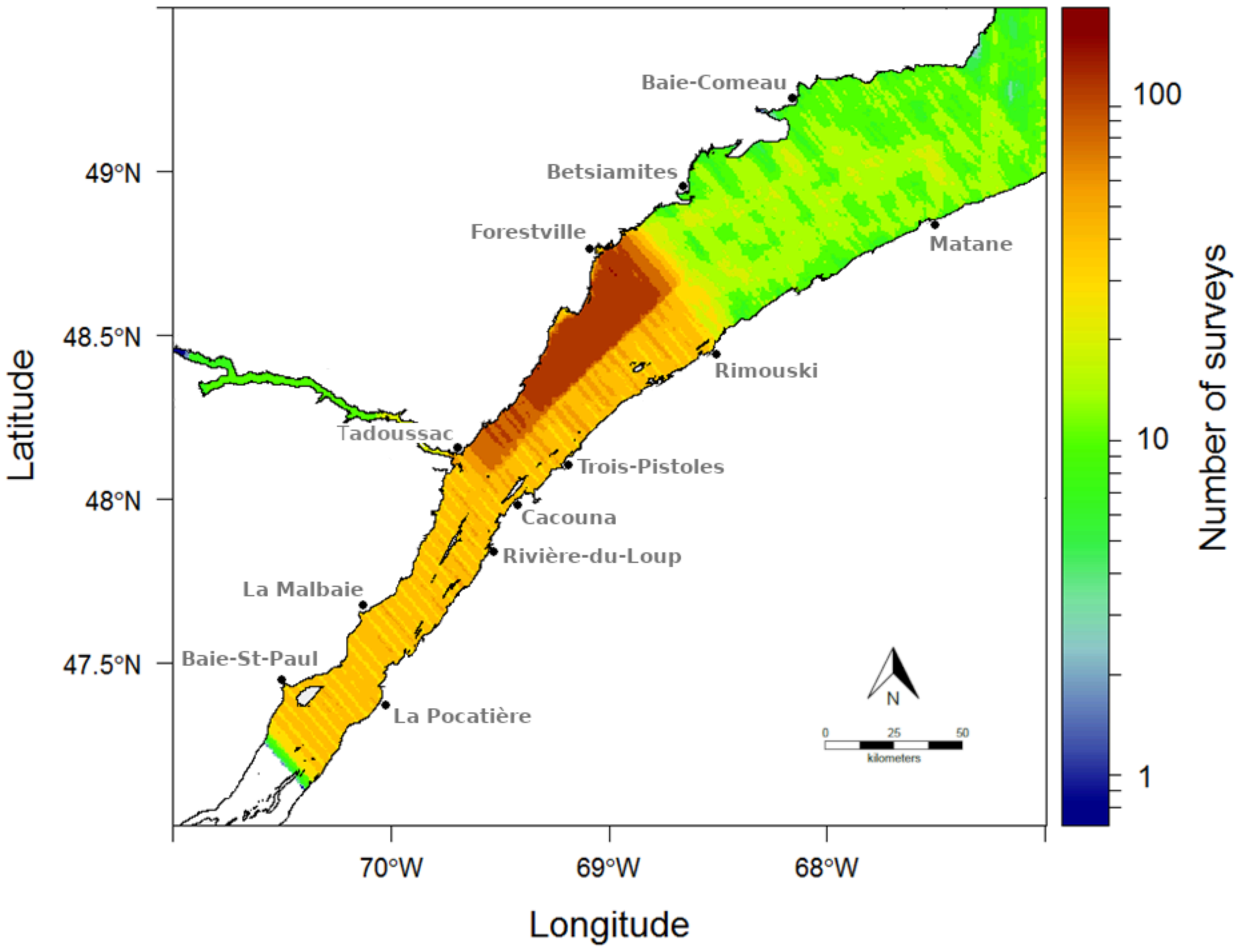


Figure 1. Effort in terms of number of aerial and boat surveys covering the St. Lawrence Estuary area from 1995 to 2017 that were used in the analyses.

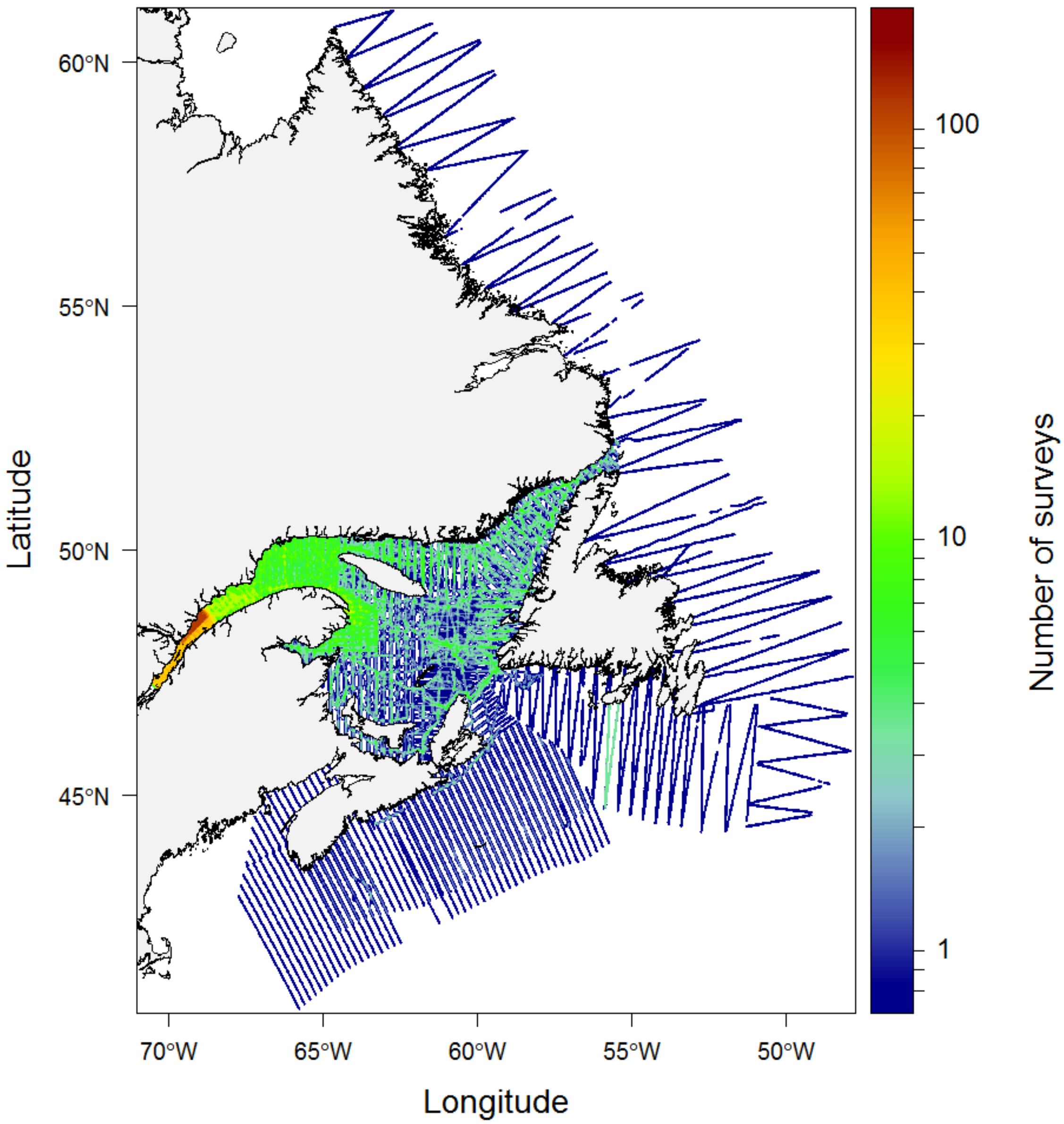


Figure 2. Effort in terms of number of aerial and boat surveys covering the Canadian Atlantic Waters from 1995 to 2017.

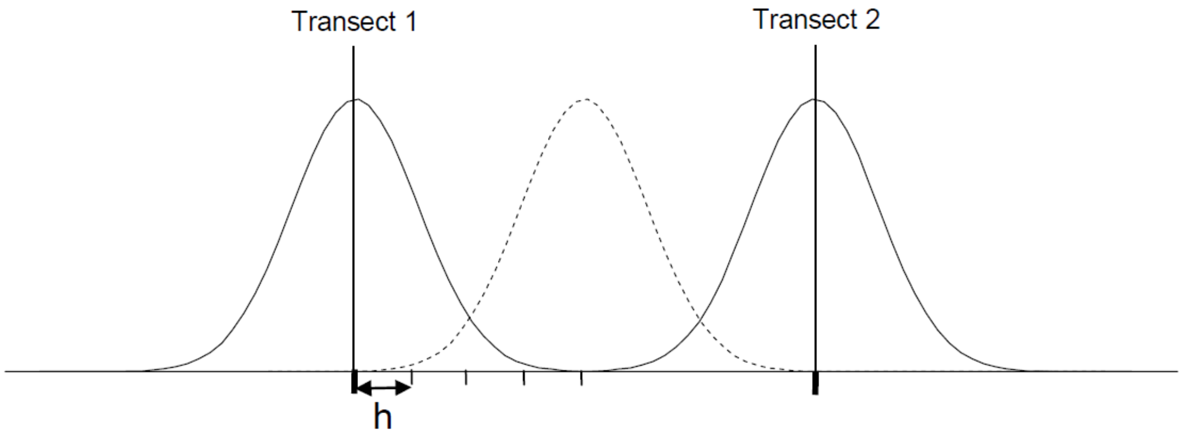


Figure 3. Two-dimensional representation of kernel smoothing of values obtained on transects. Plain line corresponds to the influence range of one observation on each transect. Dotted line show that influence does not extend beyond the other transect even if the observation is located mid-way (2.25 nautical miles for the Cetus surveys and 2 nautical miles for aerial surveys) from the two transects.

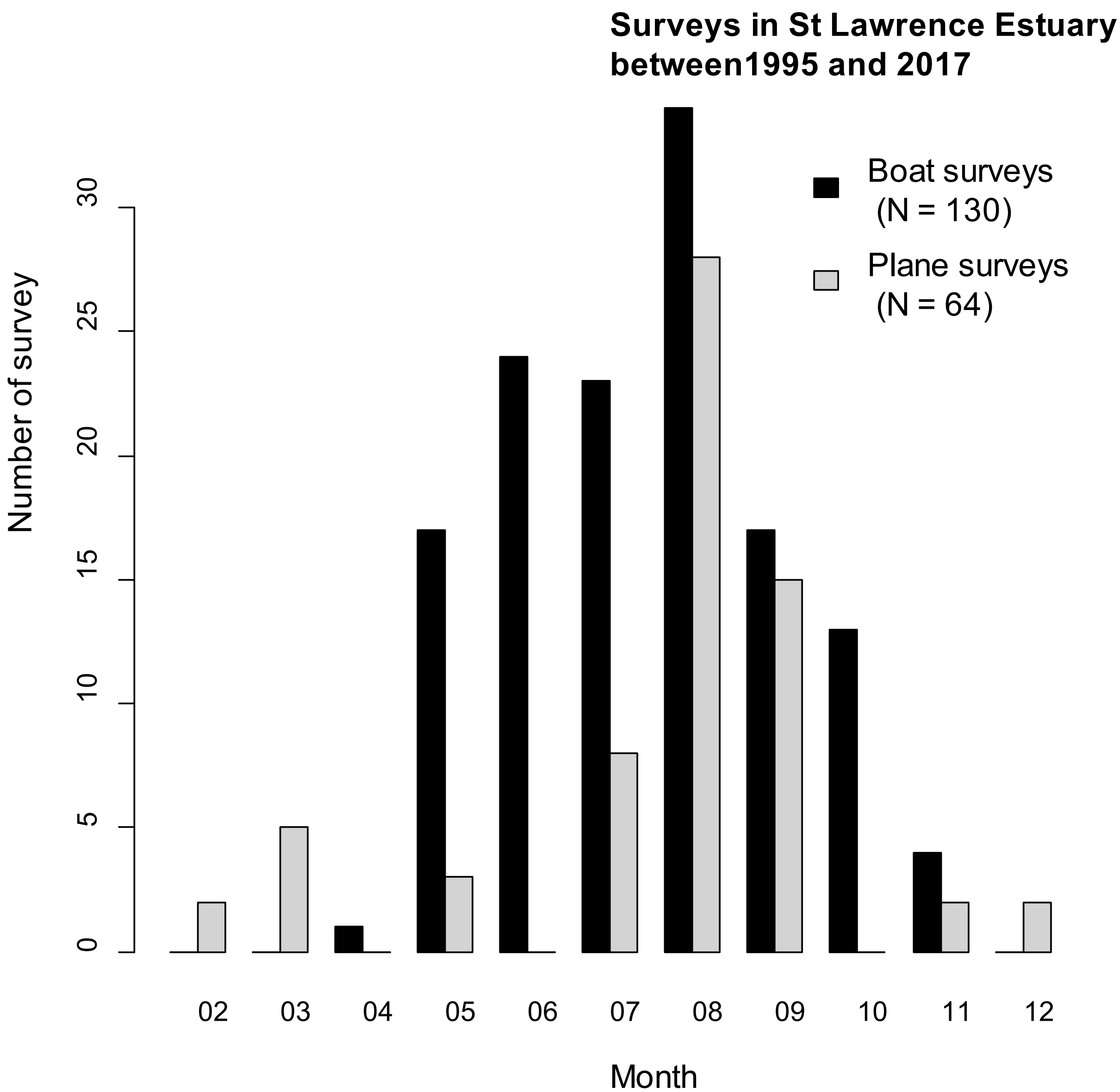


Figure 4. Monthly distribution of the boat and aerial surveys conducted by DFO between 1995 and 2017 in the St. Lawrence estuary.

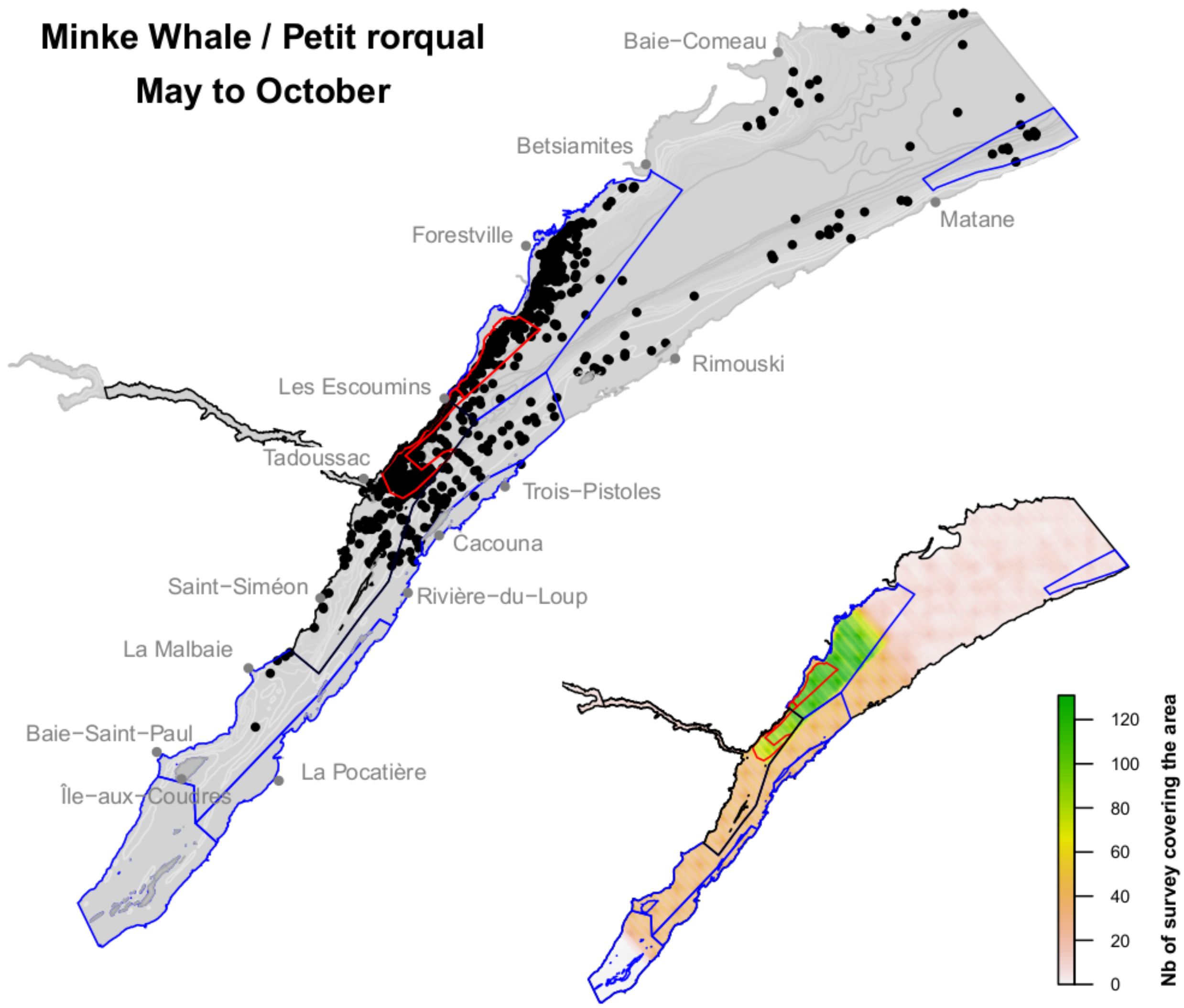


Figure 5. May to October distribution of minke whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.

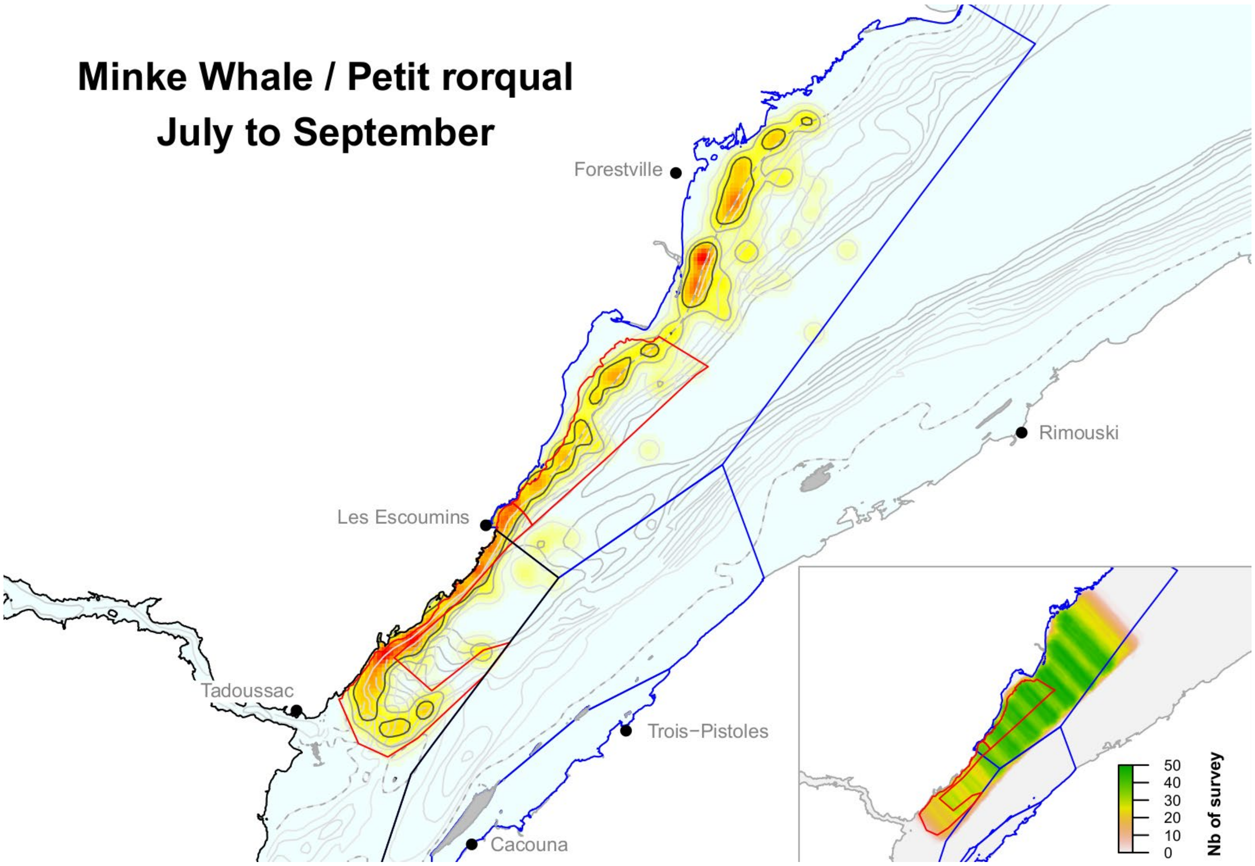


Figure 6. Kernel representation of the distribution of minke whale observations from July to September and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

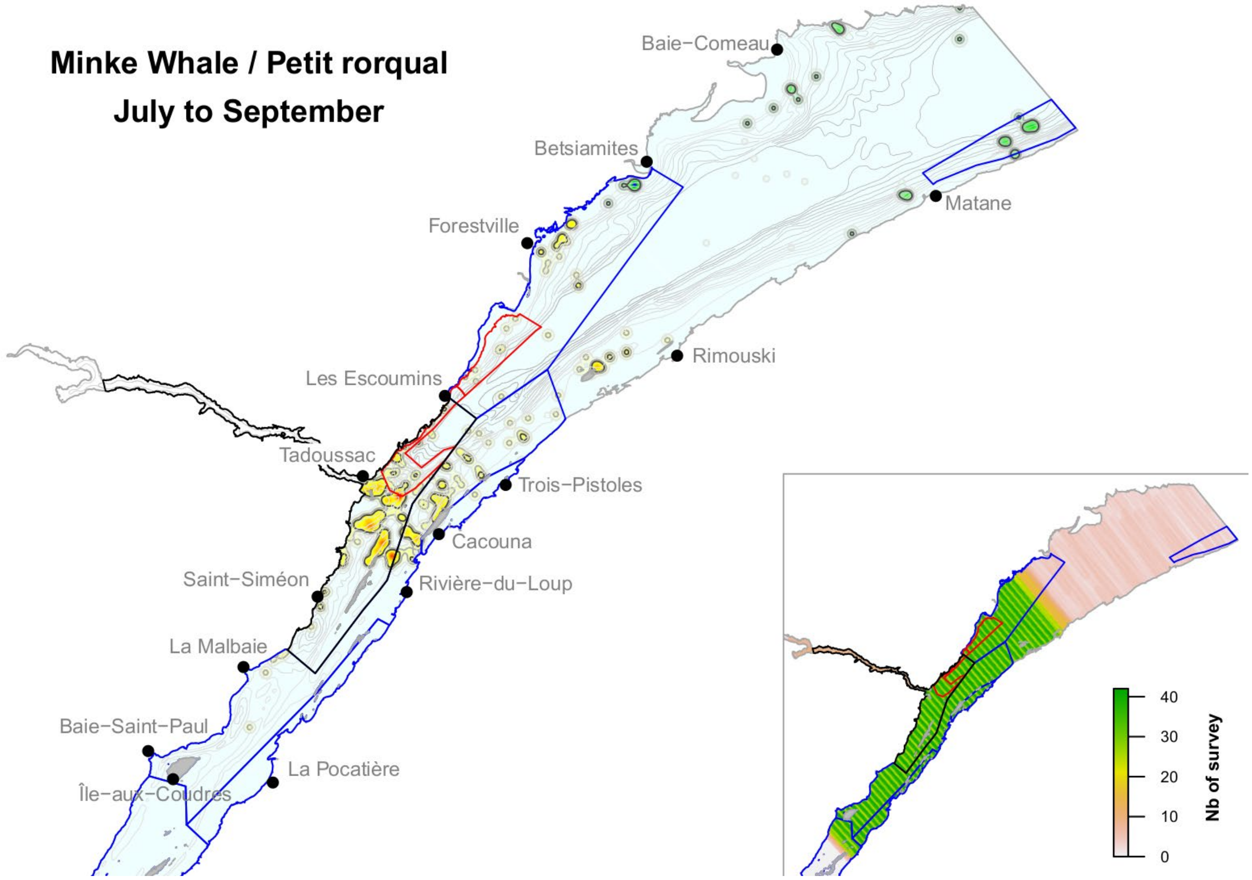


Figure 7. Kernel representation of the distribution of minke whale observations from July to September and observation effort in the St. Lawrence estuary based on the systematic aerial surveys conducted between 2001 and 2016. Note that this map regroup the results from the kernel analysis of two areas with different observation effort. Kernel representation of the zone with the higher observation effort (upstream Forestville-Rimouski) are represented with a yellow to red scale while we used a green to blue scale for the lower effort area (downstream Forestville-Rimouski). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines

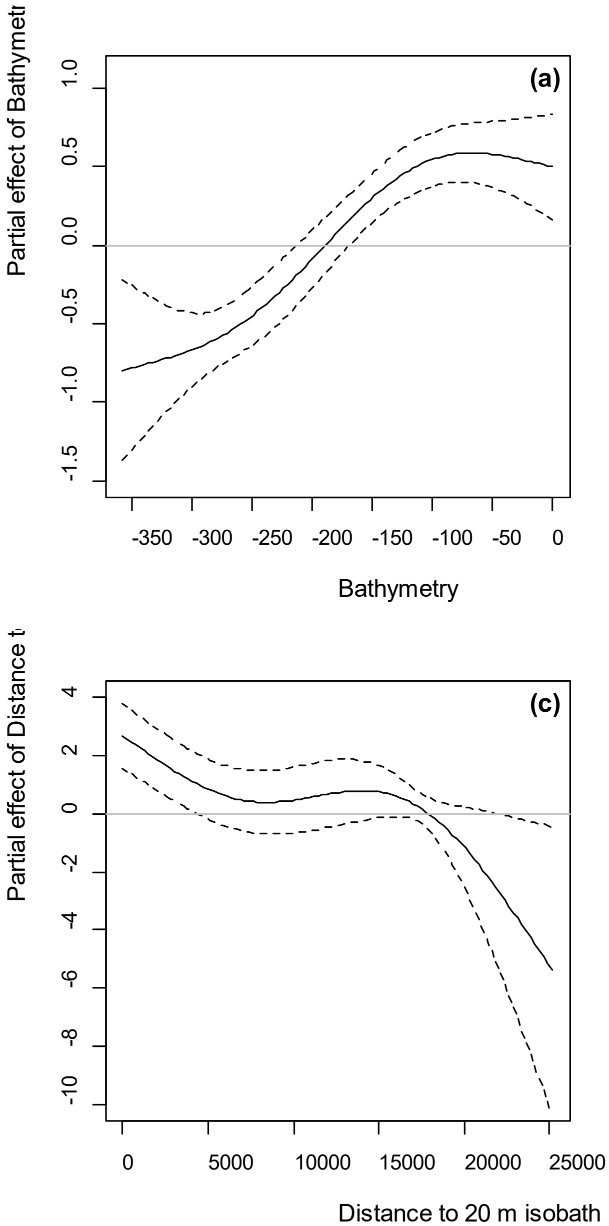


Figure 8. Smoothed relationship between the probability of occurrence of minke whale (Balaenoptera acustorostrata) and (a) Bathymetry, (b) Bottom slope and (c) Distance to 20 m isobaths. The vertical axis, expressed in logits, indicate the relative influence of each explanatory variable on the prediction. Dotted lines represent 95% confidence intervals. The horizontal grey line represents the limit between positive and negative influence of the explanatory variable on the prediction.

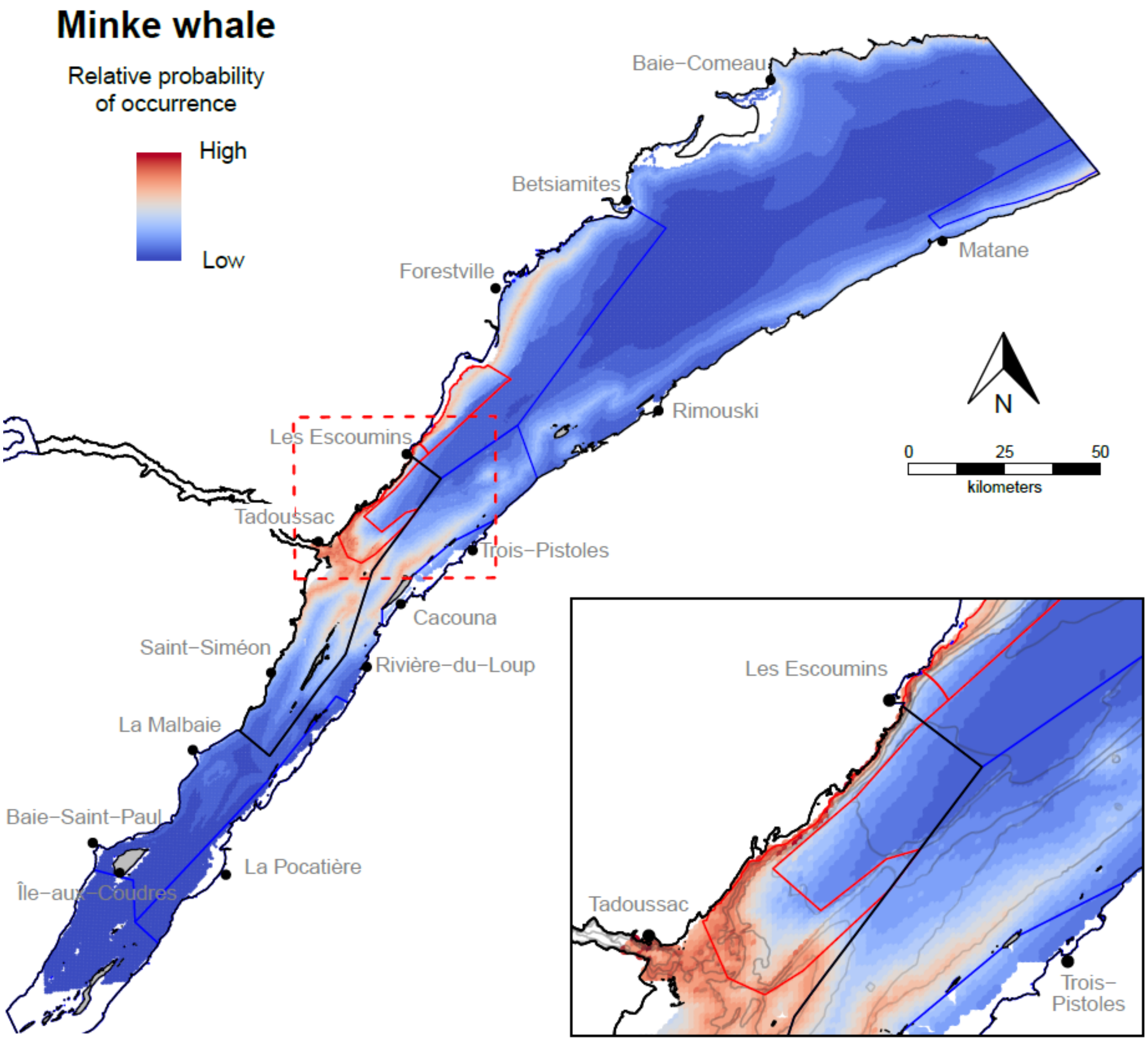


Figure 9. Predictions of the relative probability of minke whale (Balaenoptera acustorostrata) in the St. Lawrence Estuary. The model includes effect of bathymetry, bottom slope and distance to 20 m isobaths, representing areas of steeper bottom slope between coastal waters and the shelf (see also Figure 8). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.

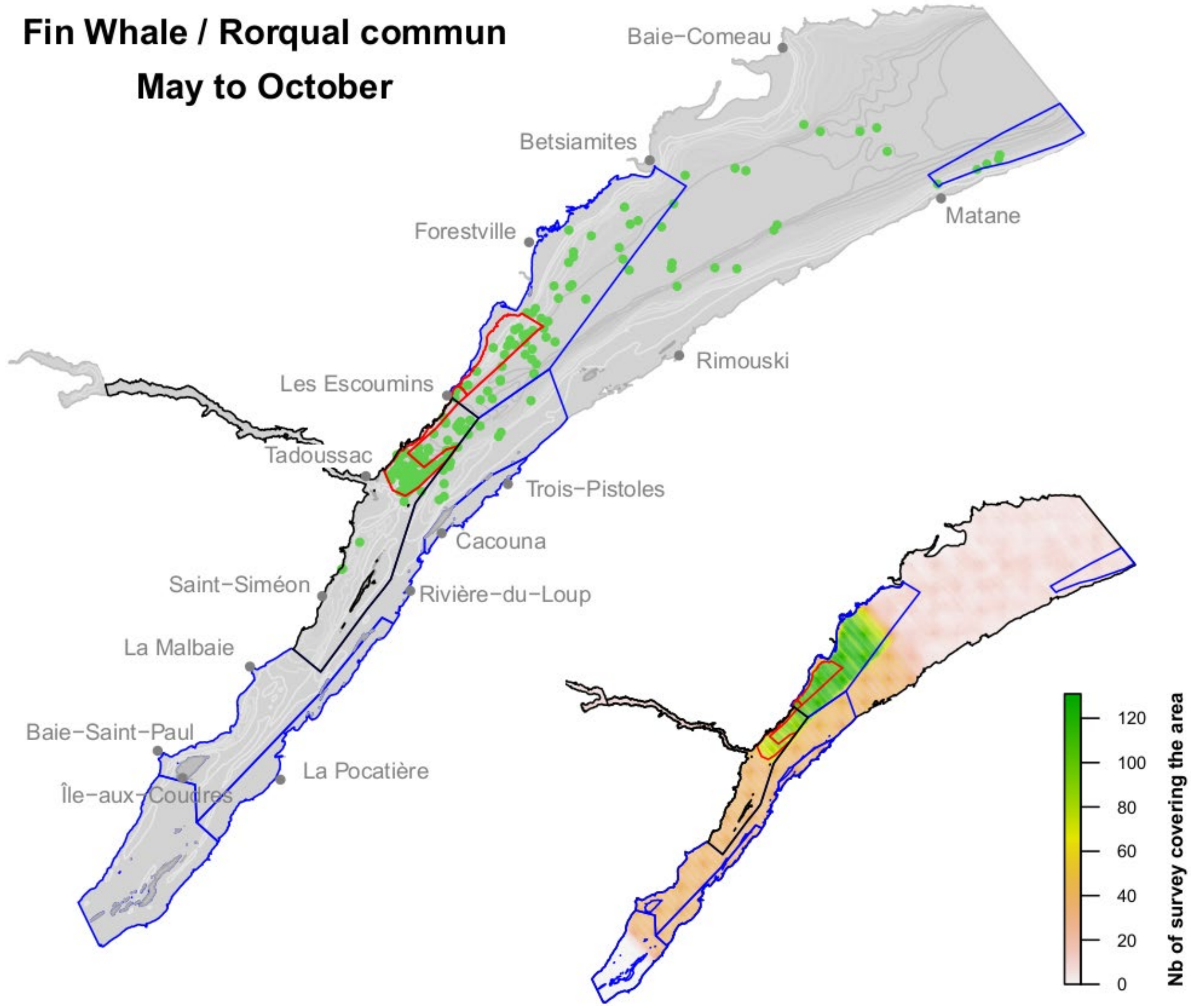


Figure 10. May to October distribution of fin whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.

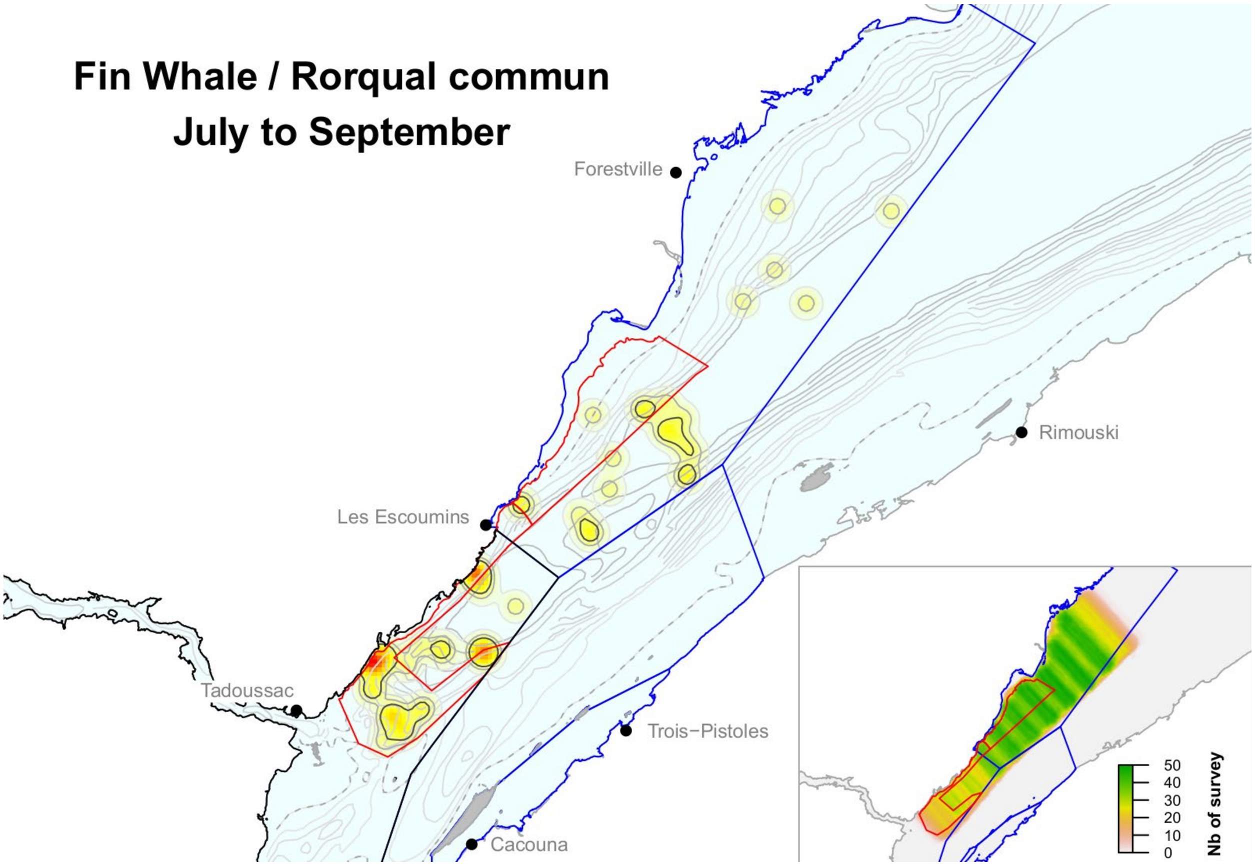


Figure 11. Kernel representation of the distribution of fin whale observations from July to September and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

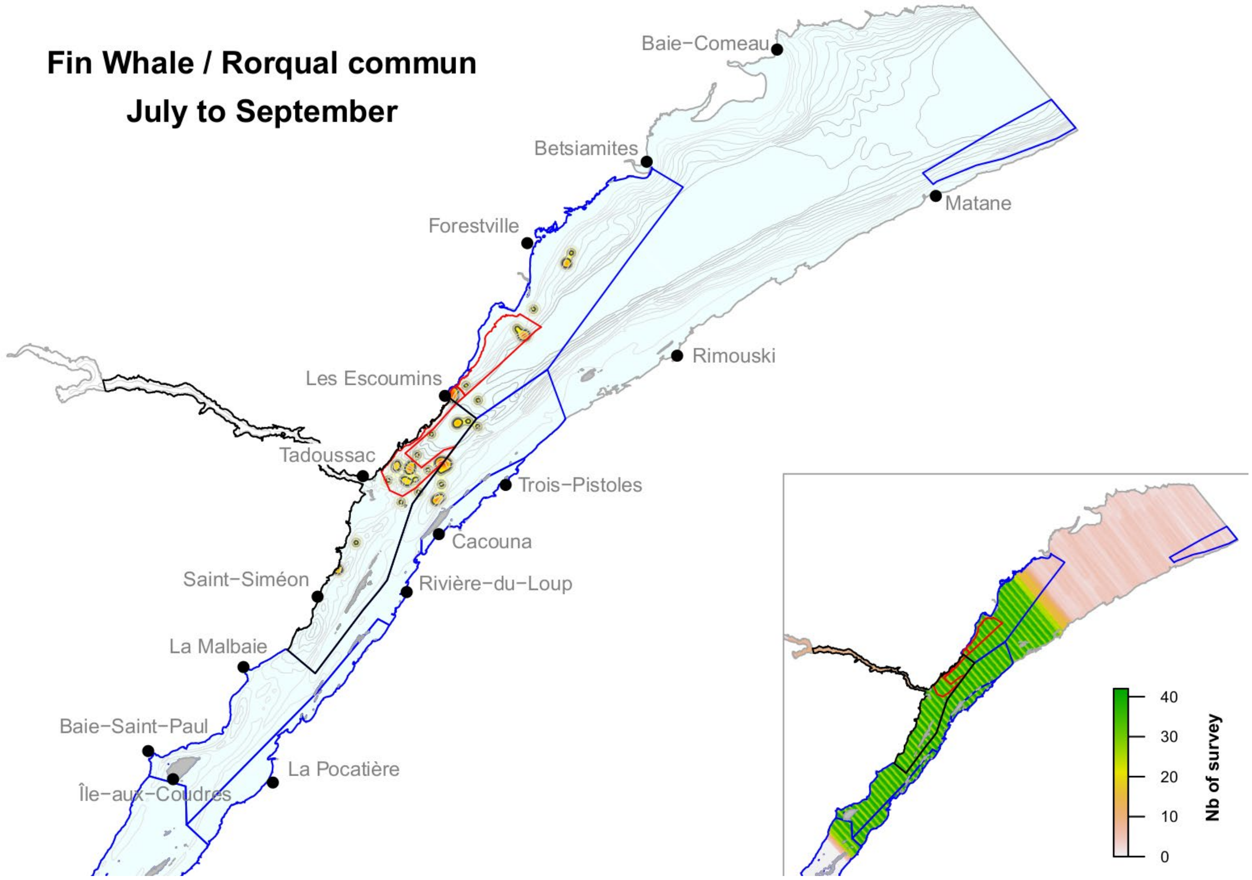


Figure 12. Kernel representation of the distribution of fin whale observations from July to September and observation effort in the St. Lawrence estuary based on the systematic aerial surveys conducted between 2001 and 2016. Note that this map regroup the results from the kernel analysis of two areas with different observation effort. Kernel representation of the zone with the higher observation effort (upstream Forestville-Rimouski) are represented with a yellow to red scale. No fin whale observation was recorded in the lower effort area (downstream Forestville-Rimouski). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

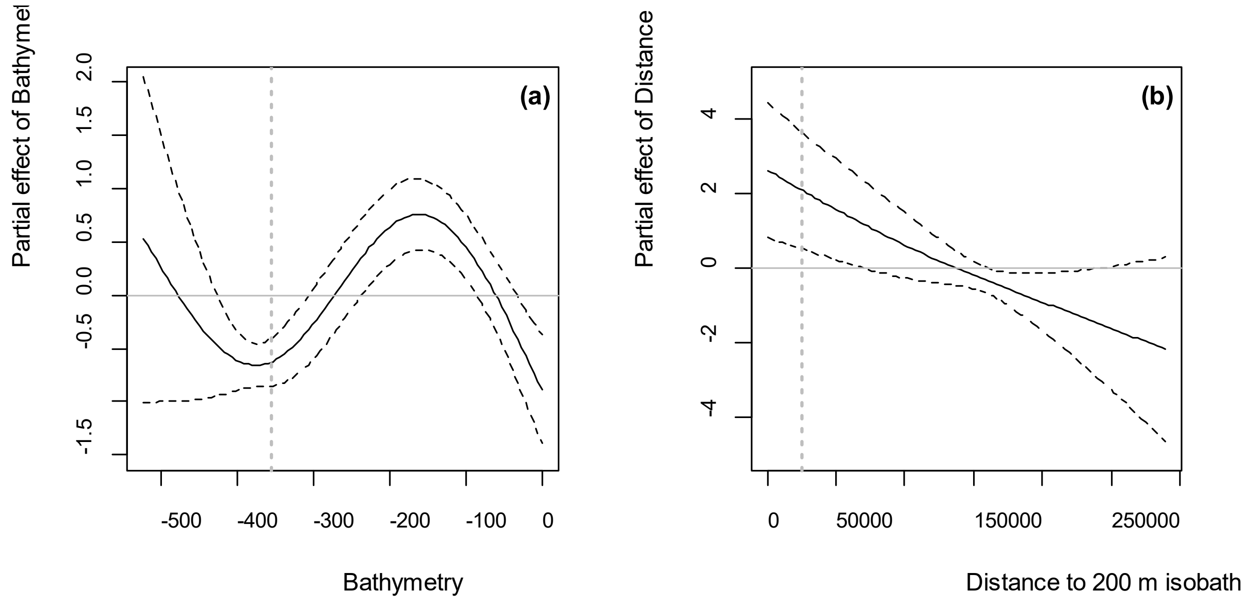


Figure 13. Smoothed relationship between the probability of occurrence of fin whale (Balaenoptera physalus) and (a) Bottom slope and (b) Distance to 200 m isobaths. The vertical axis, expressed in logits, indicate the relative influence of each explanatory variable on the prediction. Dotted lines represent 95% confidence intervals. The horizontal grey line represents the limit between positive and negative influence of the explanatory variable on the prediction and the vertical dotted line indicates the maximum value of the variable observed in the St. Lawrence Estuary.

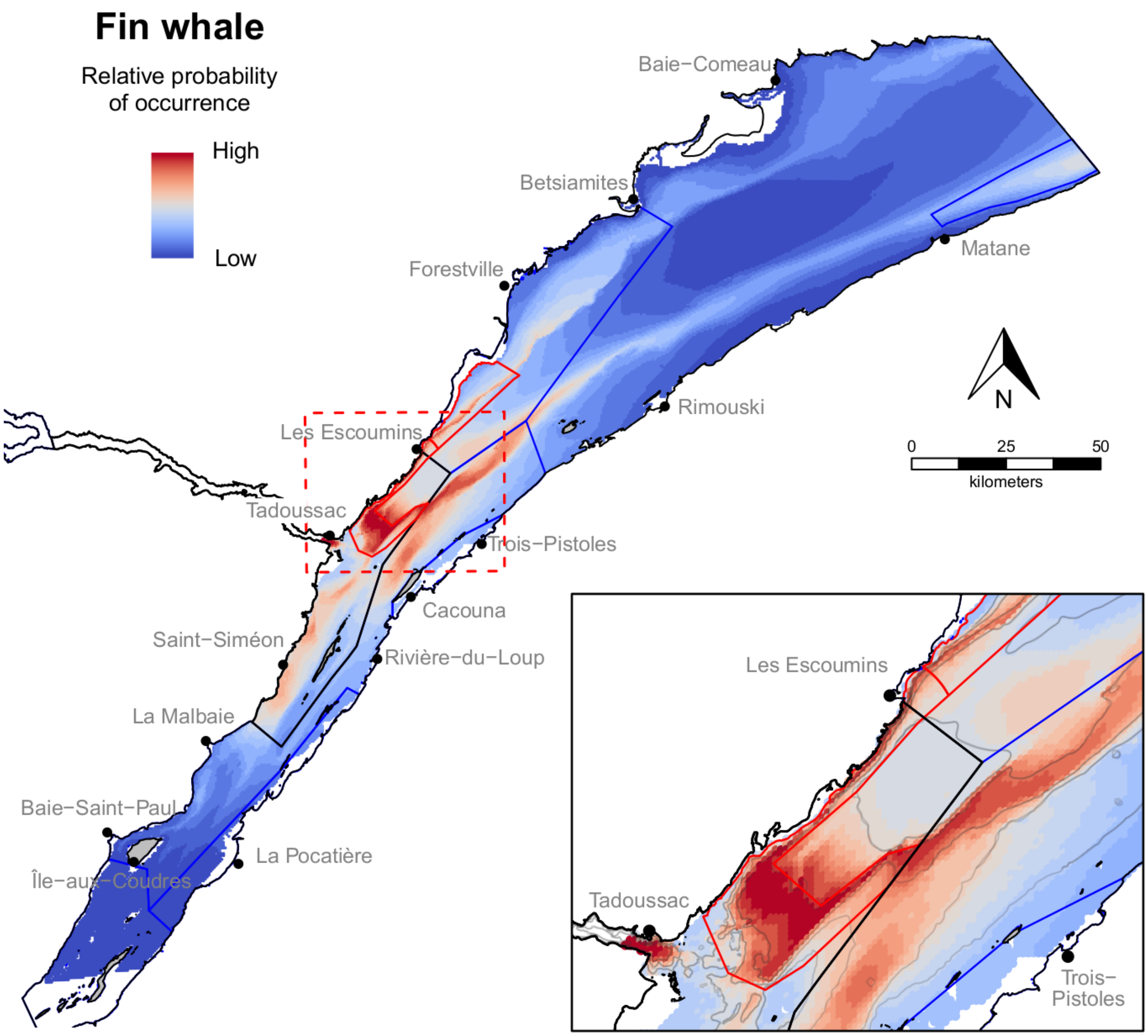


Figure 14. Predictions of the relative probability of fin whale (Balaenoptera physalus) in the St. Lawrence Estuary. The model includes effect of bottom slope and distance to 200 m isobaths, representing areas of steeper bottom slope between the shelf and the Laurentian Channel (see also Figure 13). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines

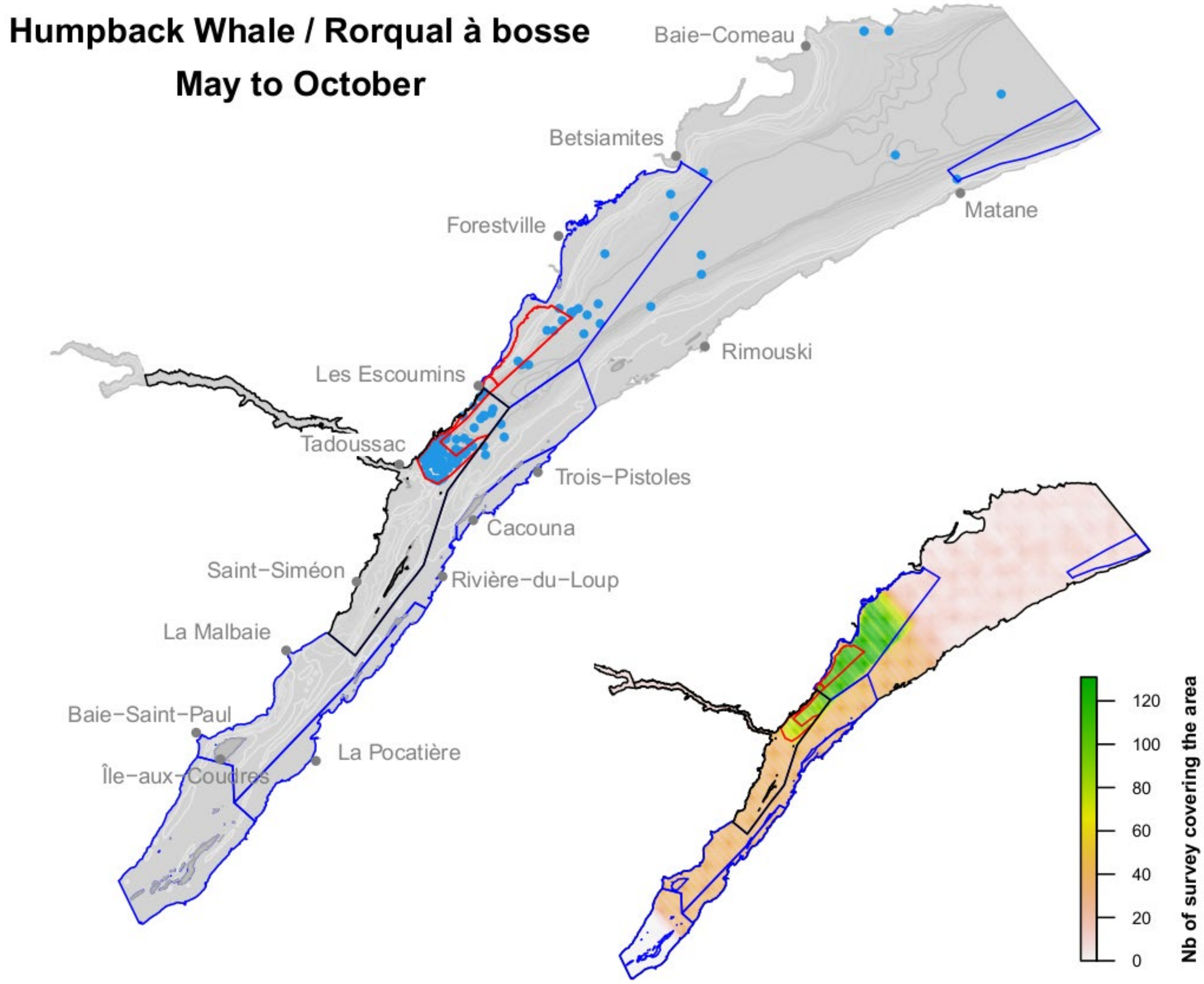


Figure 15. May to October distribution of humpback whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines

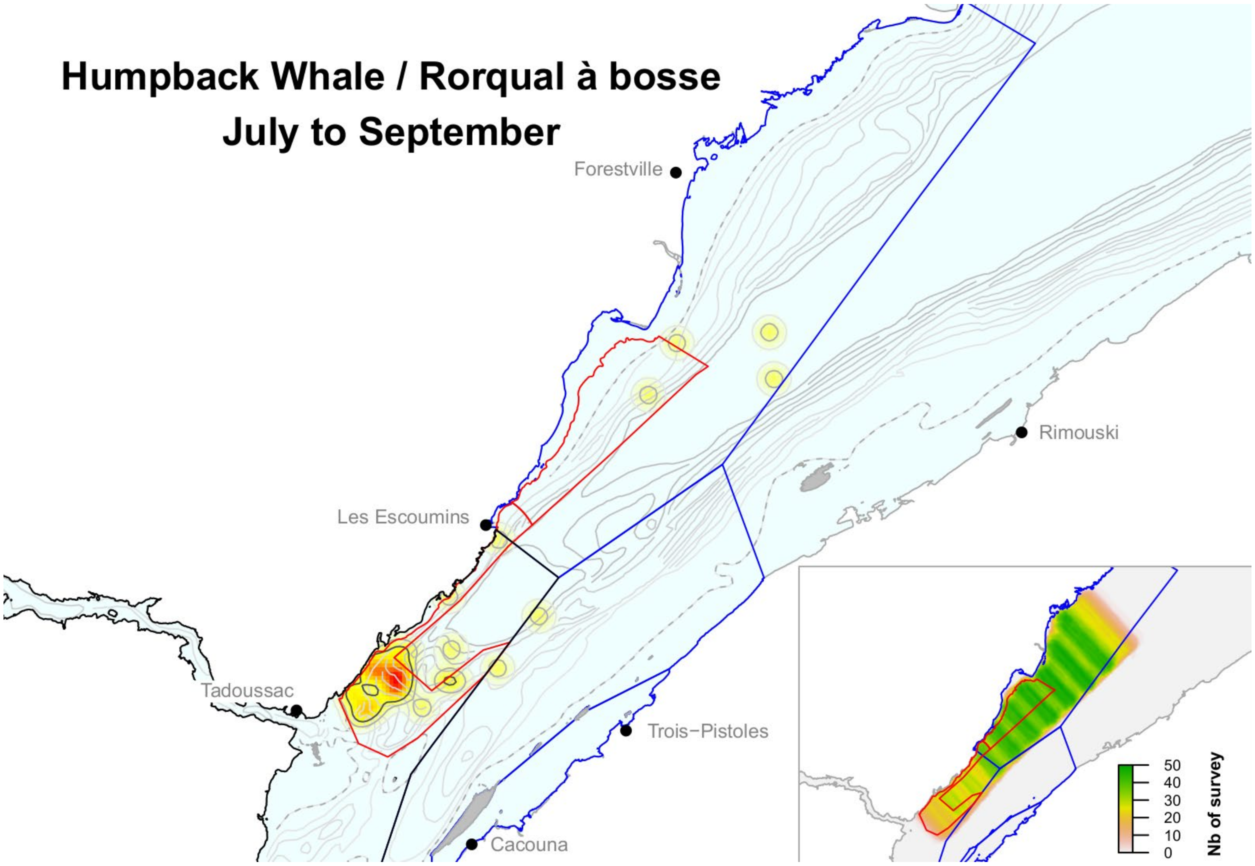


Figure 16. Kernel representation of the distribution of humpback whale observations from July to September and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

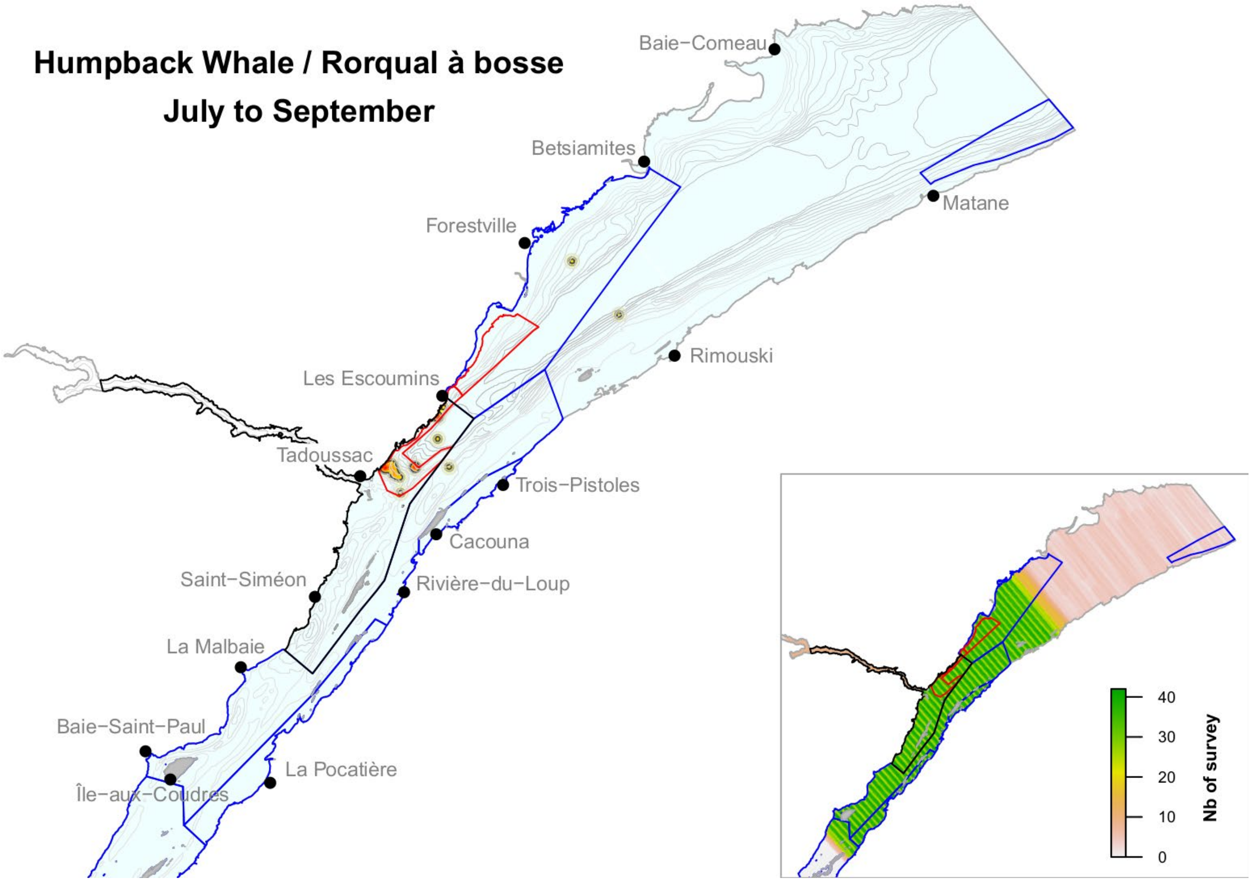


Figure 17. Kernel representation of the distribution of humpback whale observations from July to September and observation effort in the St. Lawrence estuary based on the systematic aerial surveys conducted between 2001 and 2016. Note that this map regroup the results from the kernel analysis of two areas with different observation effort. Kernel representation of the zone with the higher observation effort (upstream Forestville-Rimouski) are represented with a yellow to red scale. No humpback whale observation was recorded in the lower effort area (downstream Forestville-Rimouski). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.

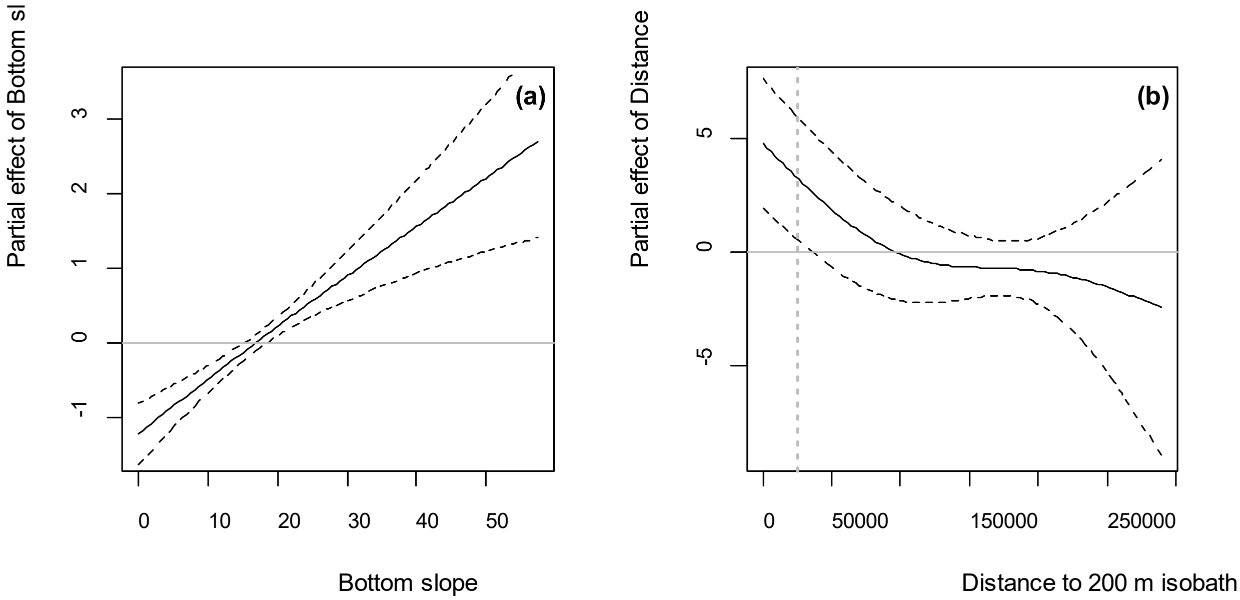


Figure 18. Smoothed relationship between the probability of occurrence of humpback whale (Megaptera novaeangliae) and (a) Bottom slope and (b) Distance to 200 m isobaths. The vertical axis, expressed in logits, indicate the relative influence of each explanatory variable on the prediction. Dotted lines represent 95% confidence intervals. The horizontal grey line represents the limit between positive and negative influence of the explanatory variable on the prediction.

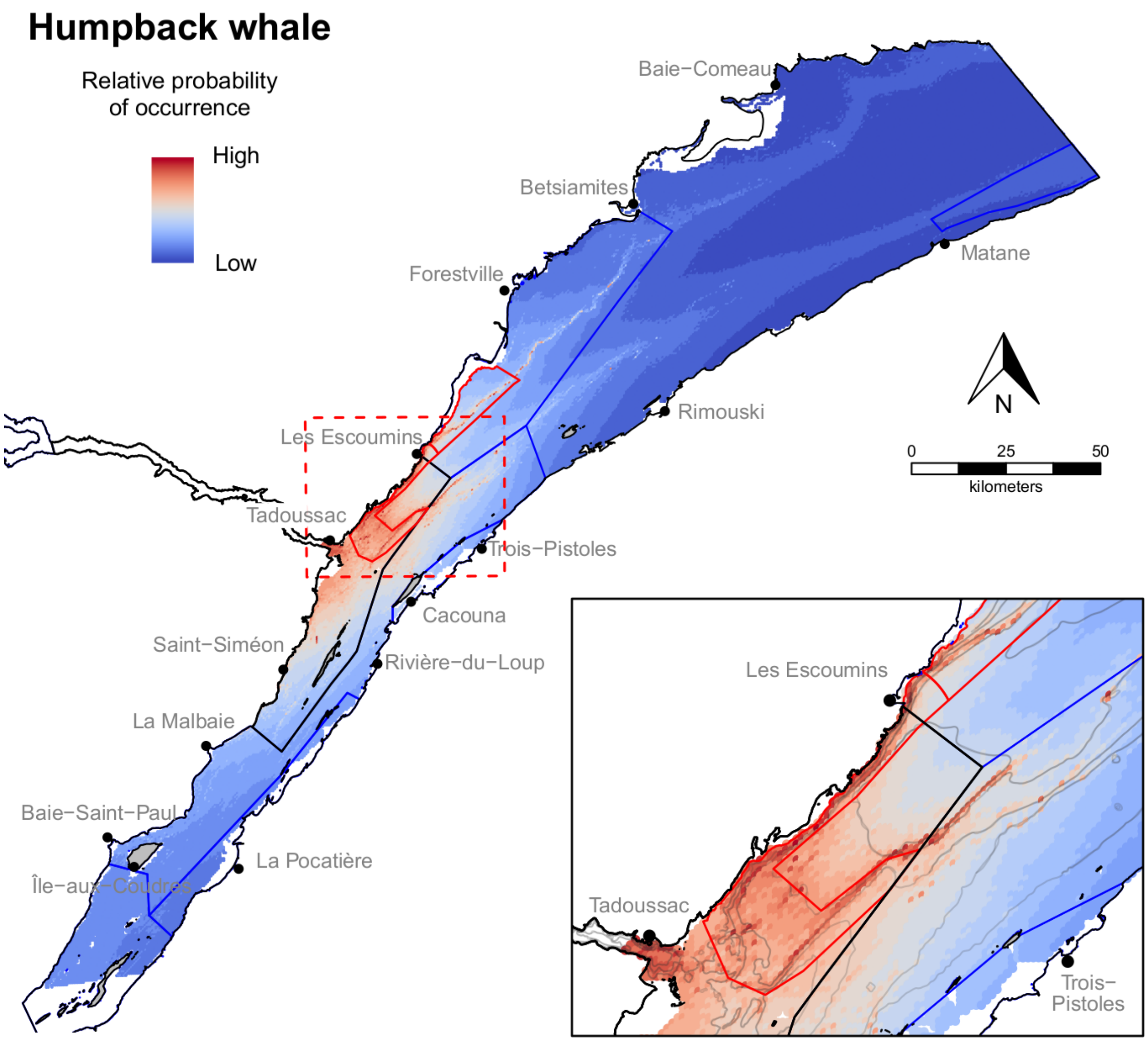


Figure 19. Predictions of the relative probability of humpback whale (Megaptera novaeangliae) in the St. Lawrence Estuary. The model includes effect of bottom slope and distance to 200 m isobaths, representing areas of steeper bottom slope between the shelf and Laurentian Channel (see also Figure 18).The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines

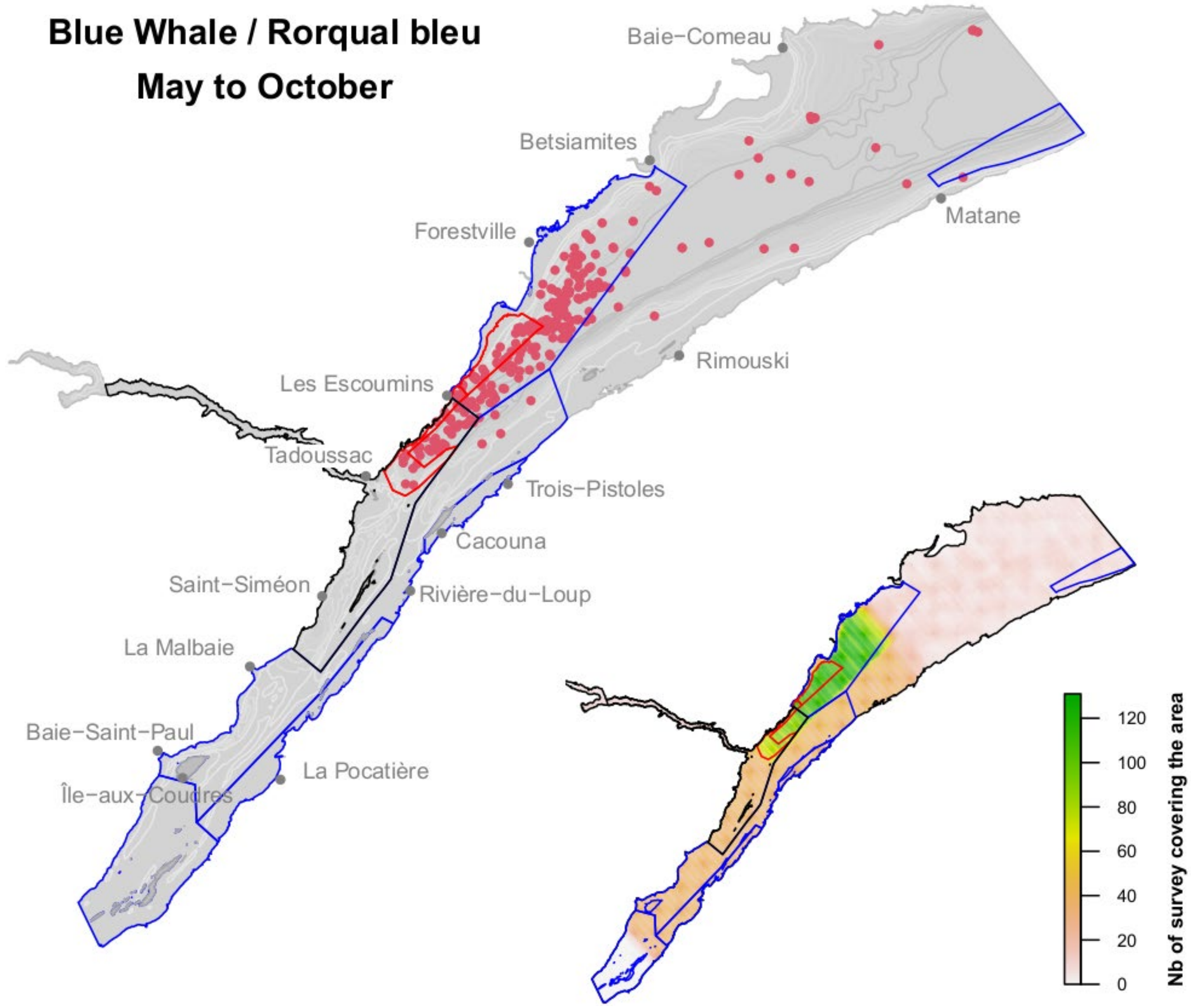


Figure 20. May to October distribution of humpback whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.

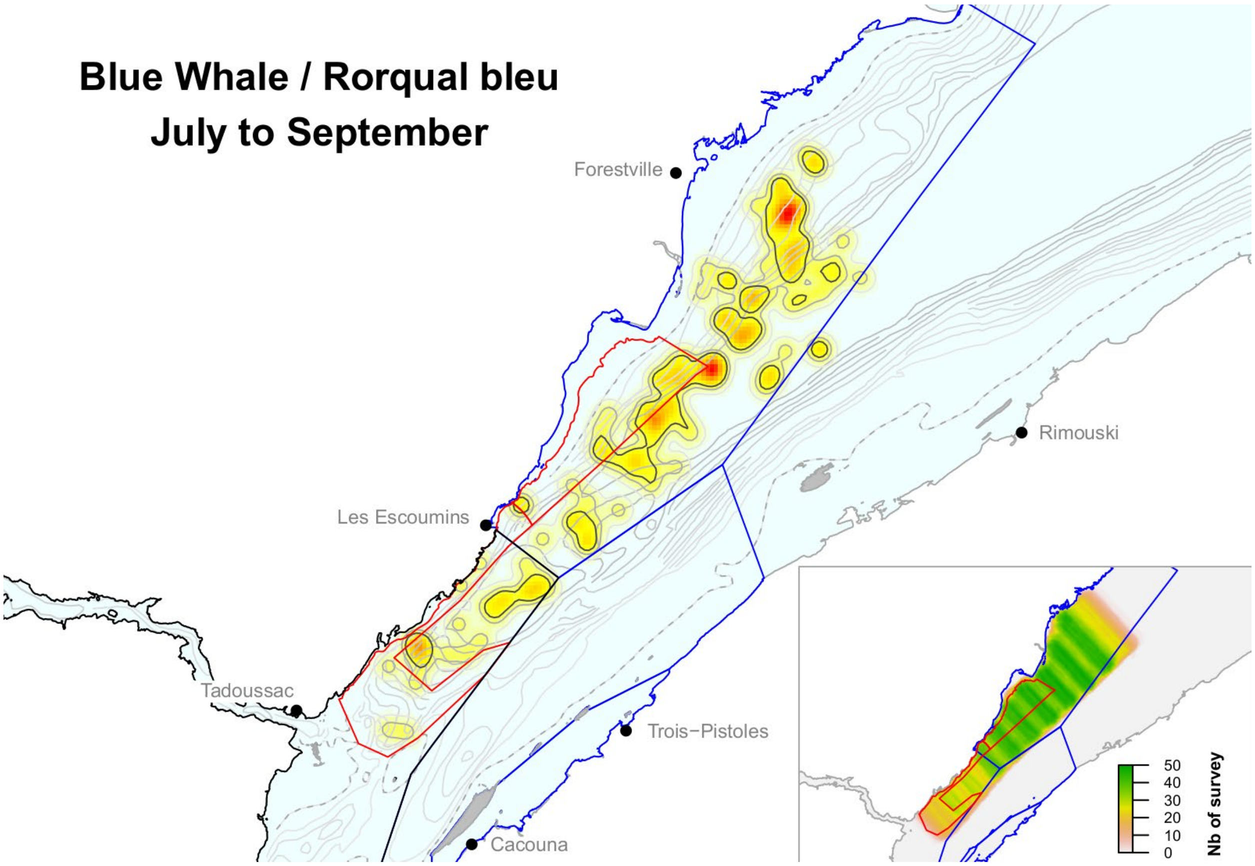


Figure 21. Kernel representation of the distribution of blue whale observations from July to September and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

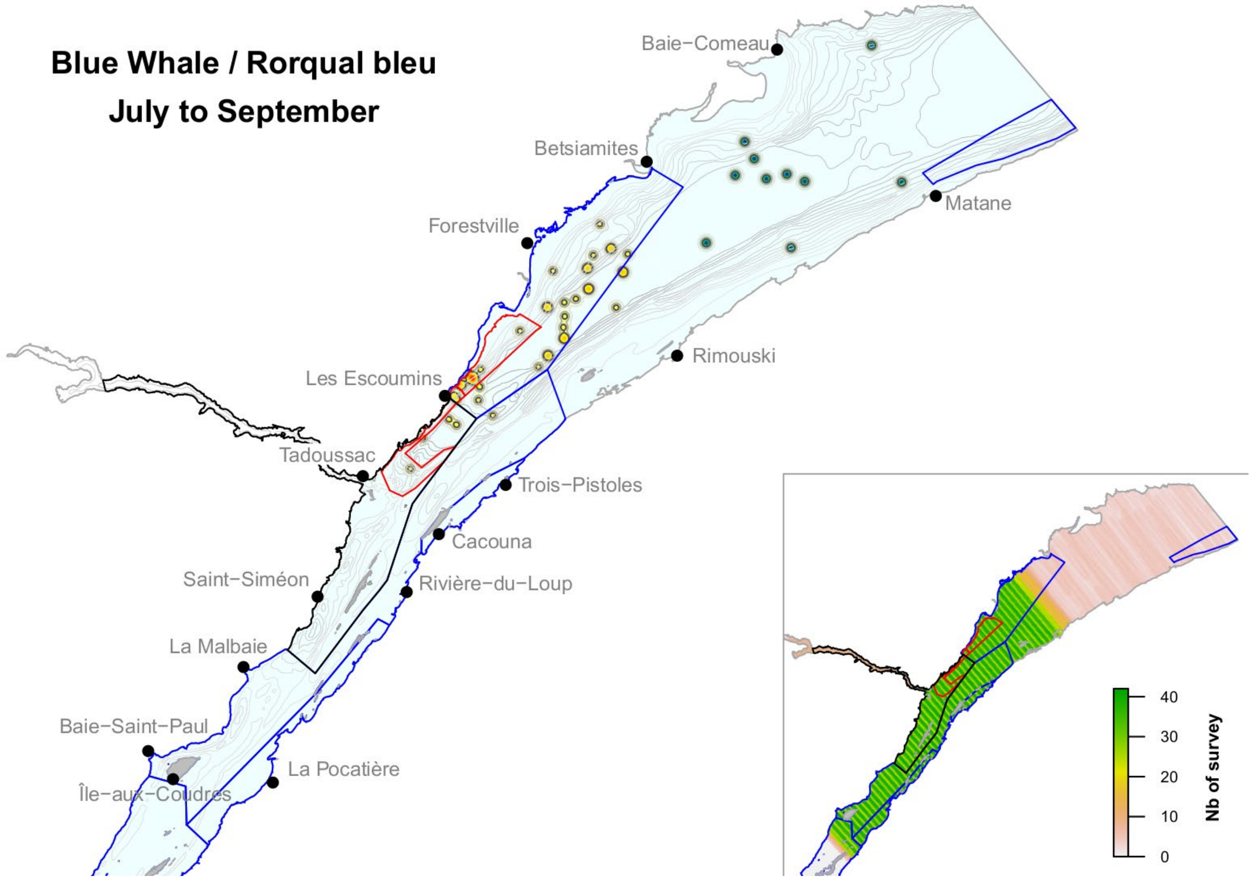


Figure 22. Kernel representation of the distribution of blue whale observations from July to September and observation effort in the St. Lawrence estuary based on the systematic aerial surveys conducted between 2001 and 2016. Note that this map regroup the results from the kernel analysis of two areas with different observation effort. Kernel representation of the zone with the higher observation effort (upstream Forestville-Rimouski) are represented with a yellow to red scale while we used a green to blue scale for the lower effort area (downstream Forestville-Rimouski). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.

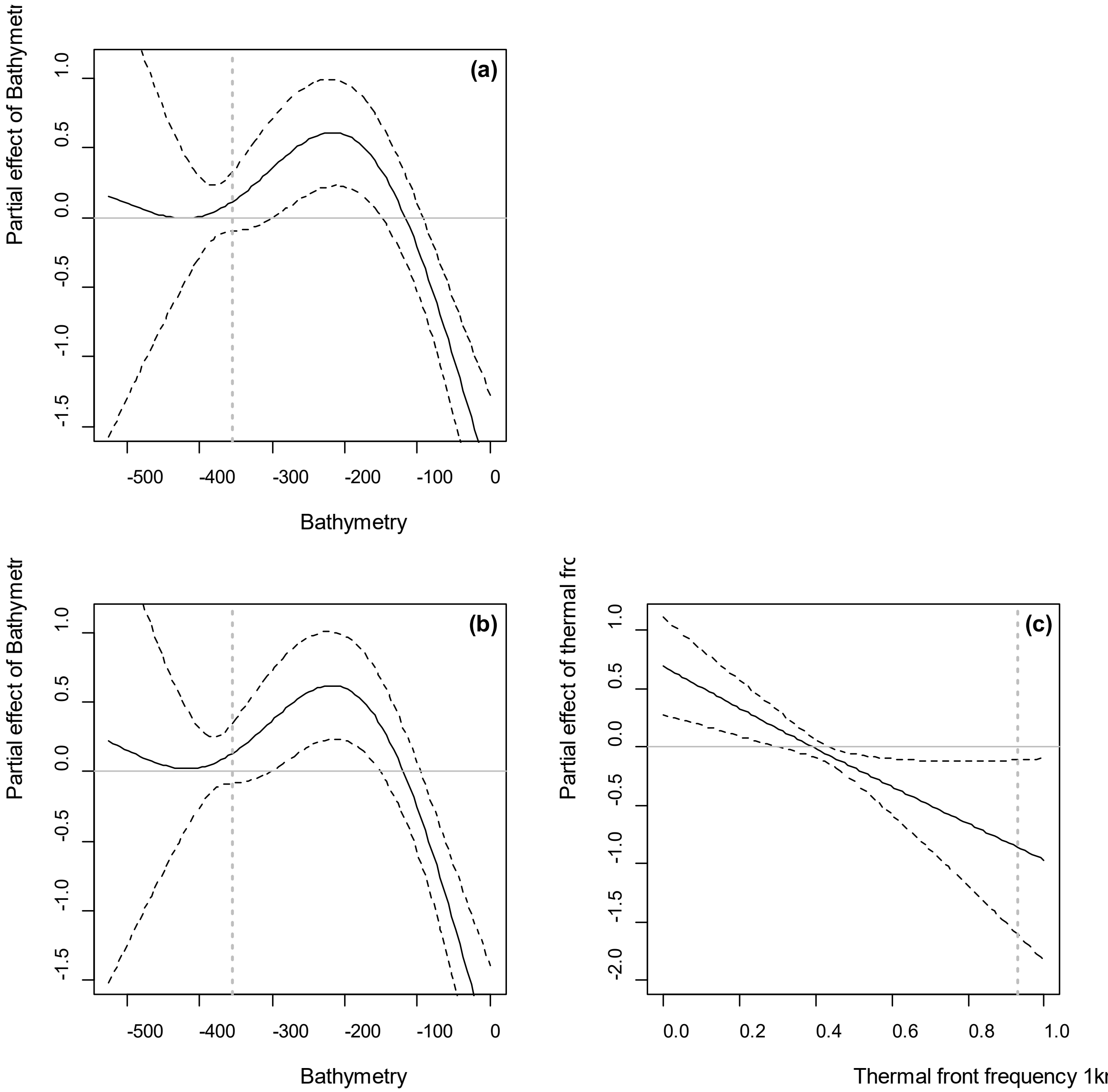


Figure 23. Smoothed relationship between the probability of occurrence of blue whale (Balaenoptera physalus) and (a) Bathymetry or (b) Bathymetry and (c) Mean thermal front frequency 1 km around the location. The vertical axis, expressed in logits, indicate the relative influence of each explanatory variable on the prediction. Dotted lines represent 95% confidence intervals. The horizontal grey line represents the limit between positive and negative influence of the explanatory variable on the prediction and the vertical dotted line indicates the maximum value of the variable observed in the St. Lawrence Estuary.

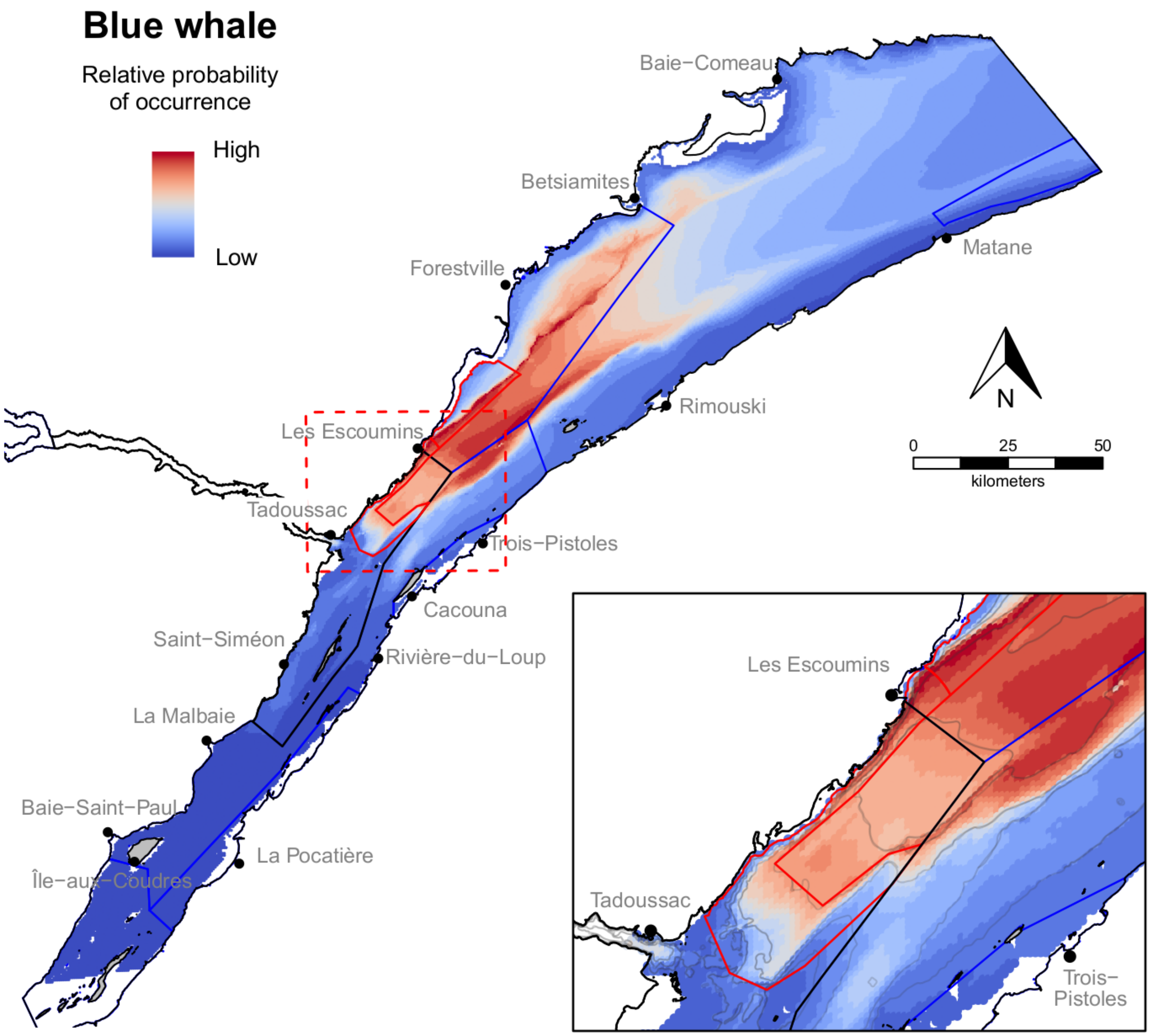
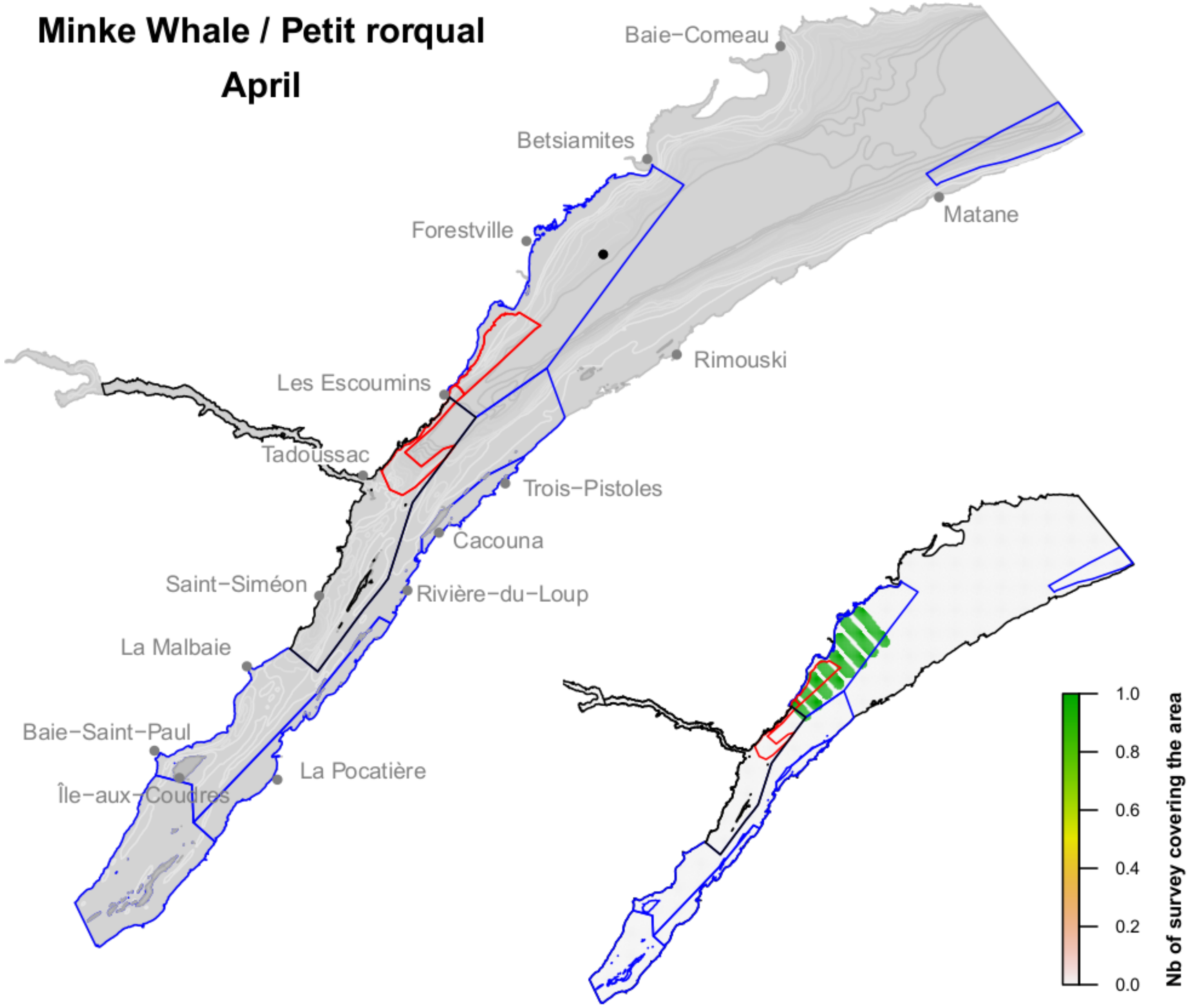
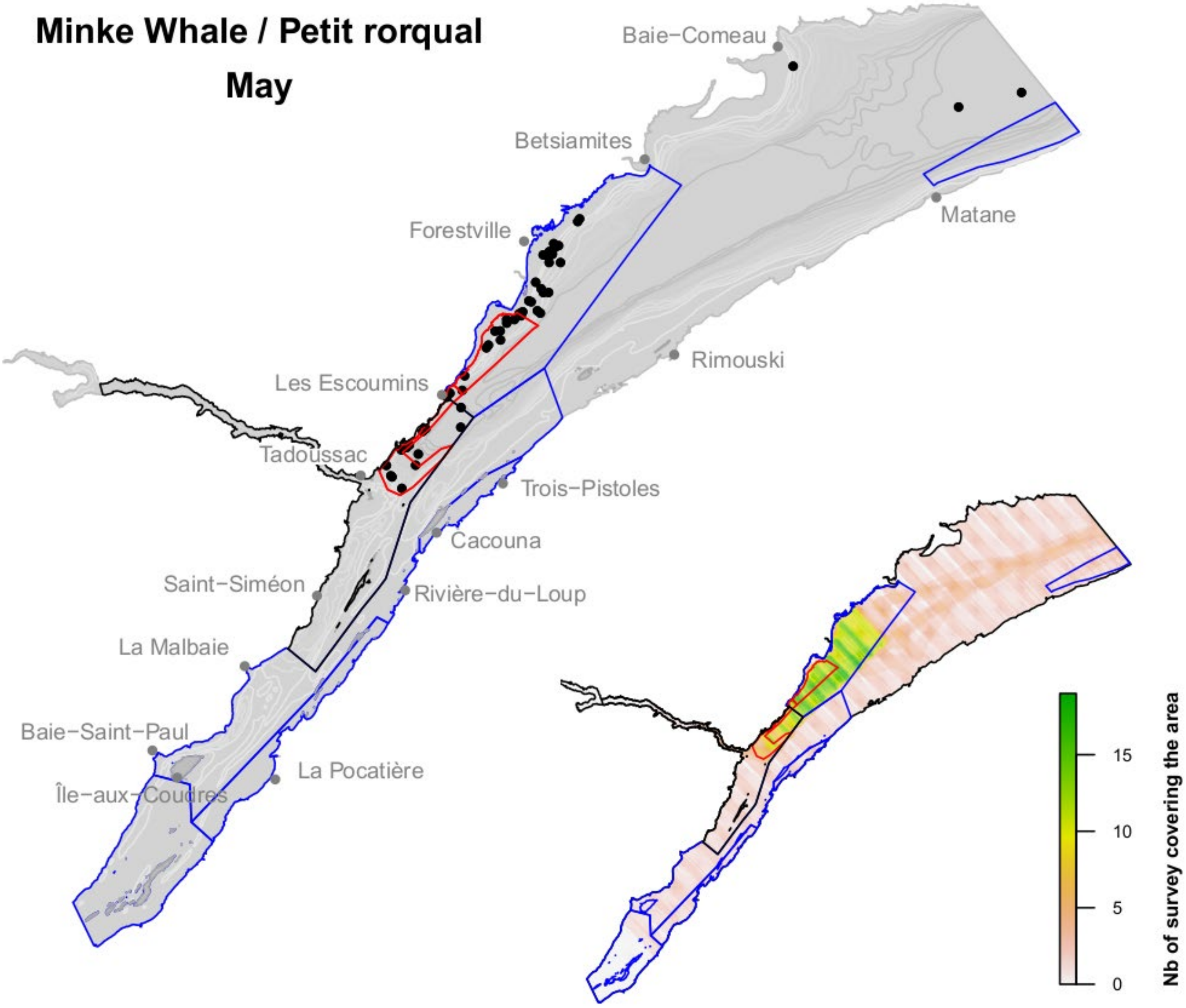


Figure 24. Predictions of the relative probability of blue whale (Balaenoptera physalus) in the St. Lawrence Estuary. The model includes only the effect of bathymetry (see also Figure 23). The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines

APPENDICES



Appendix 1. Monthly distribution of minke whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines



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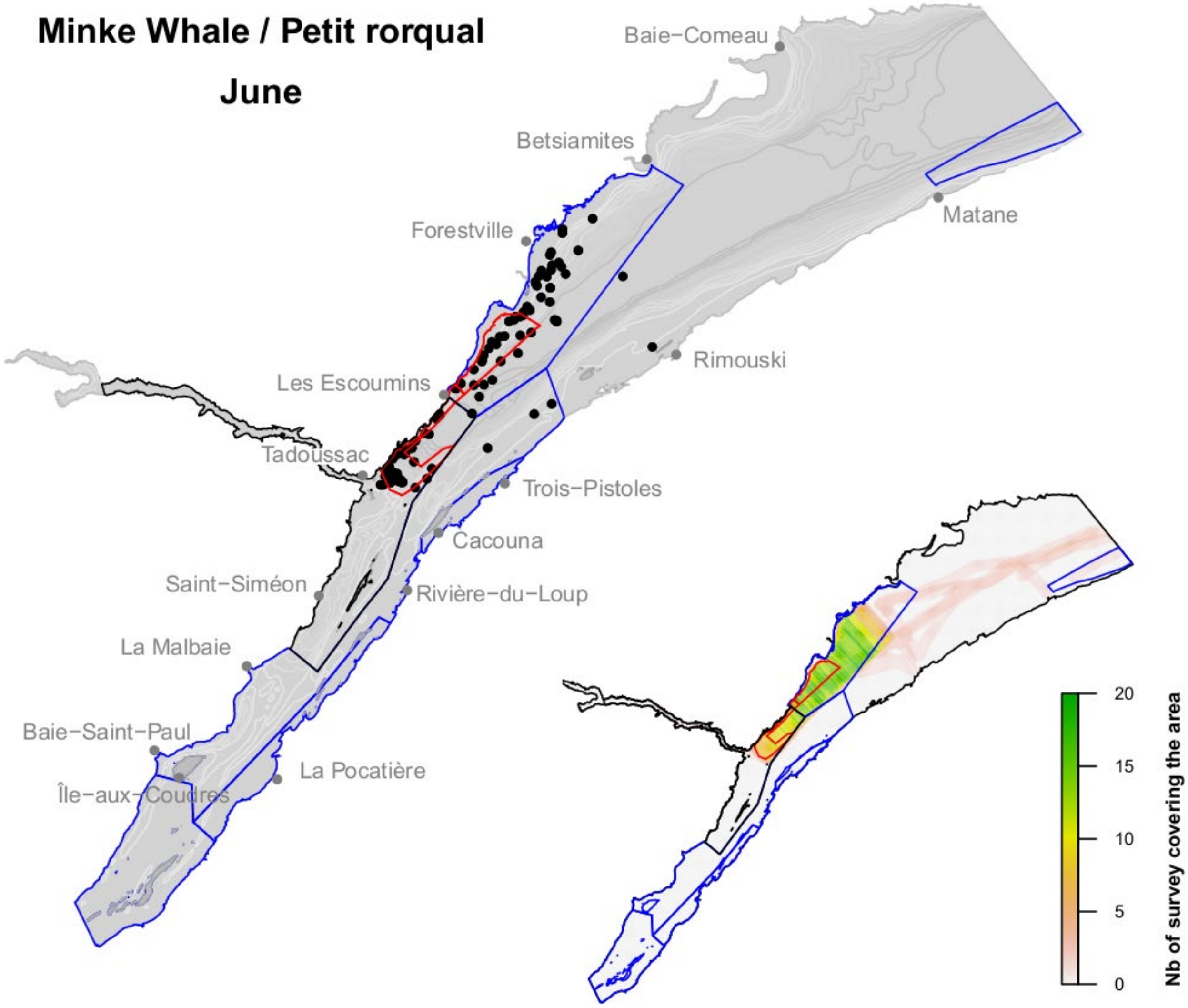

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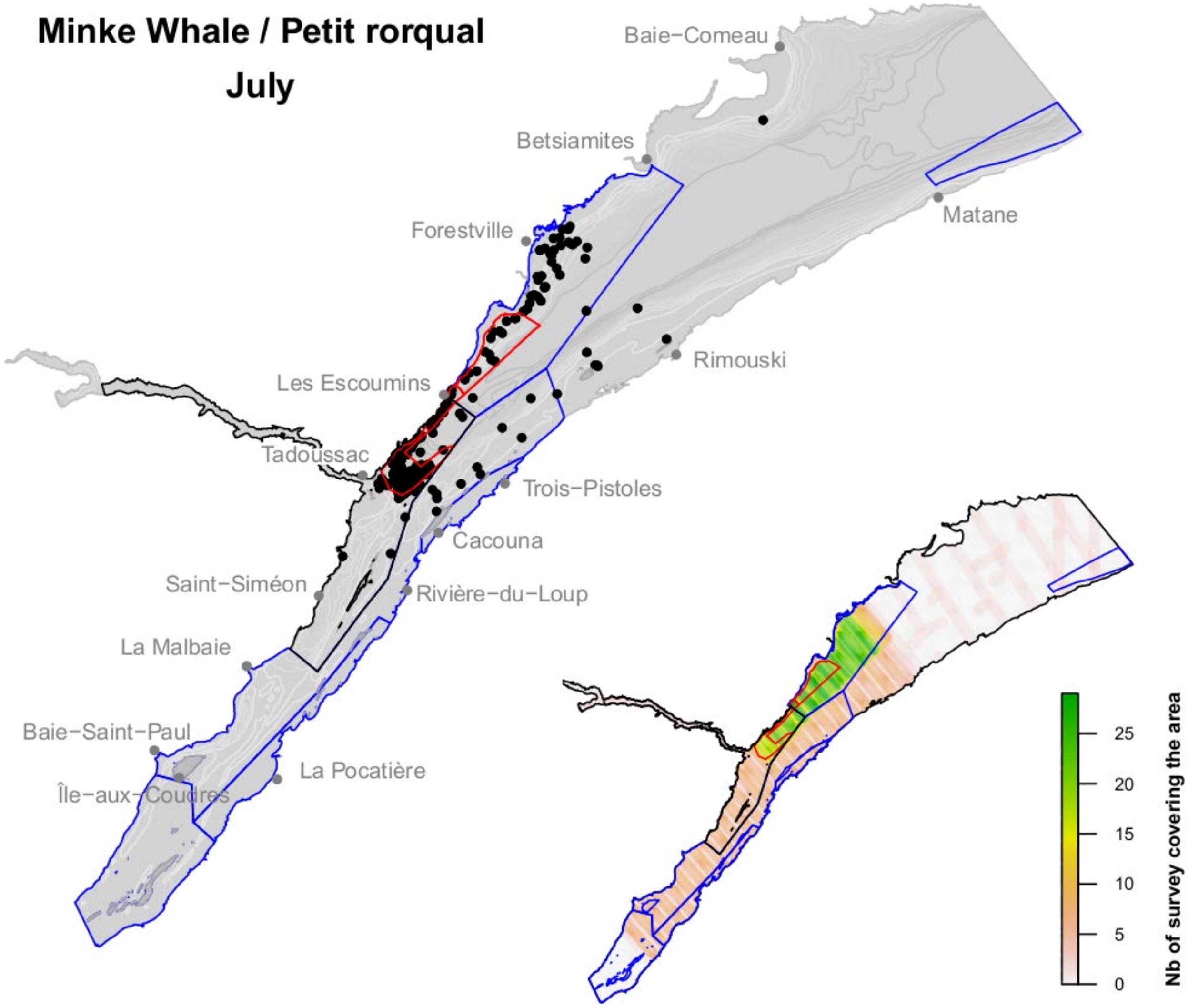

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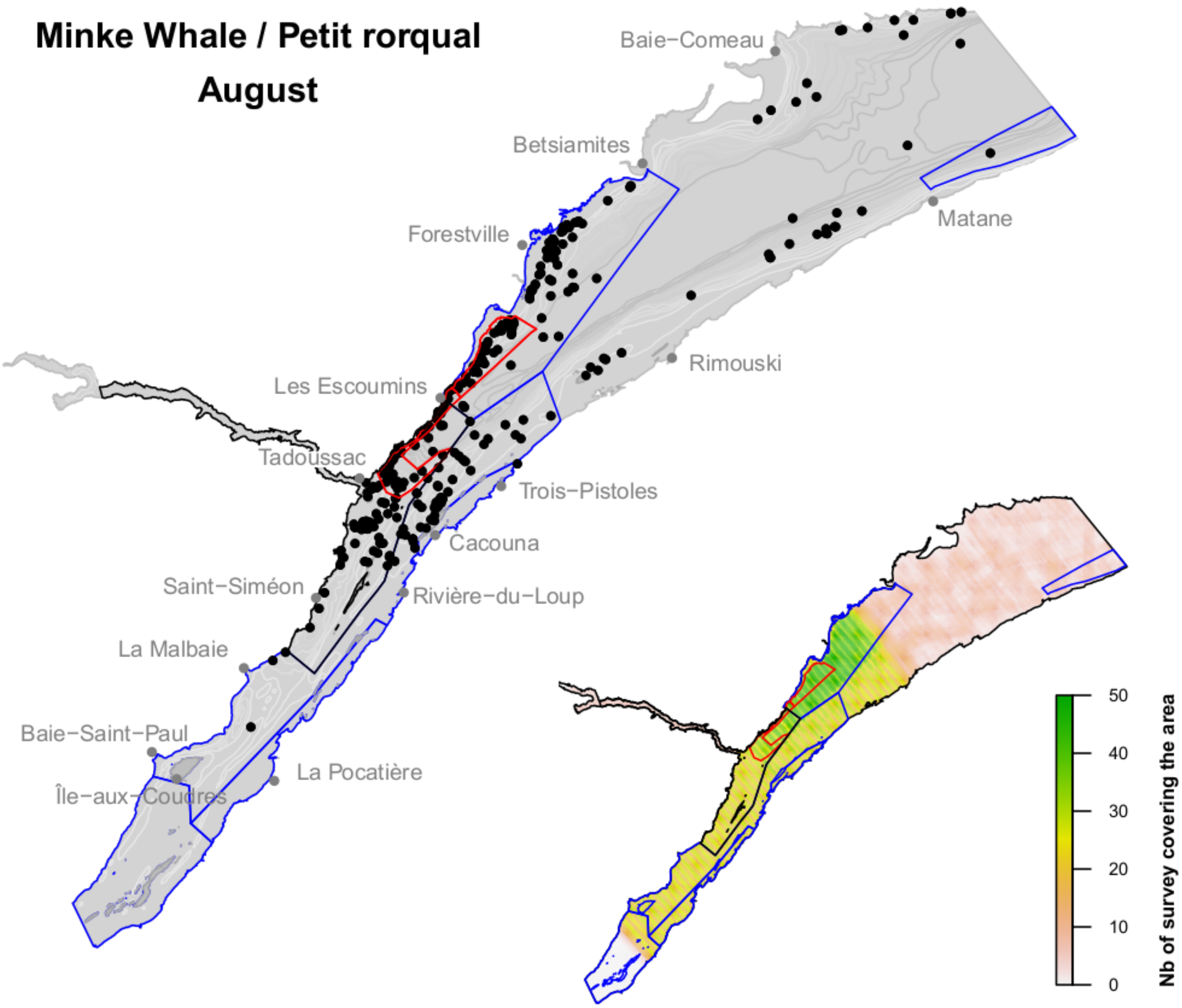

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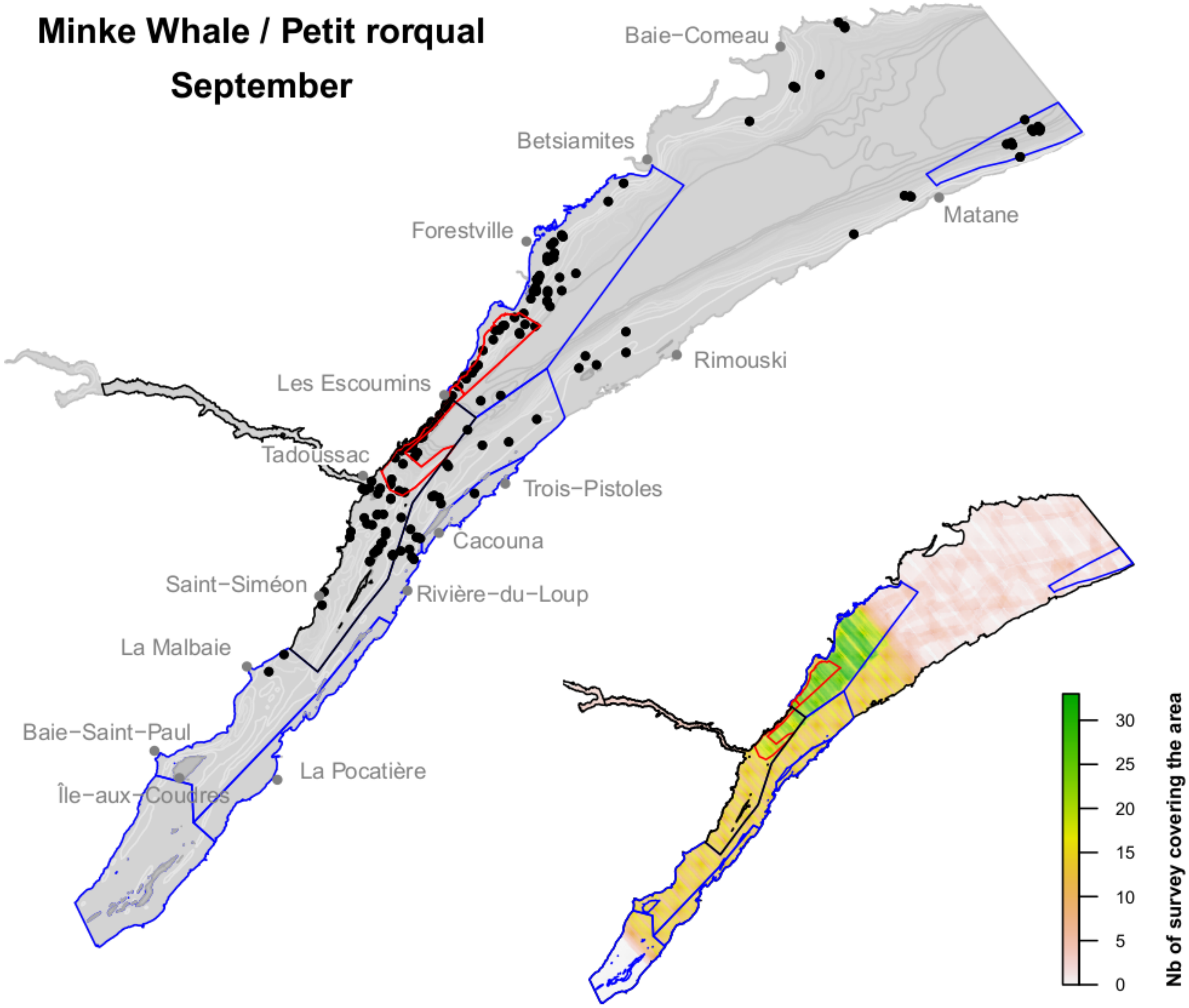

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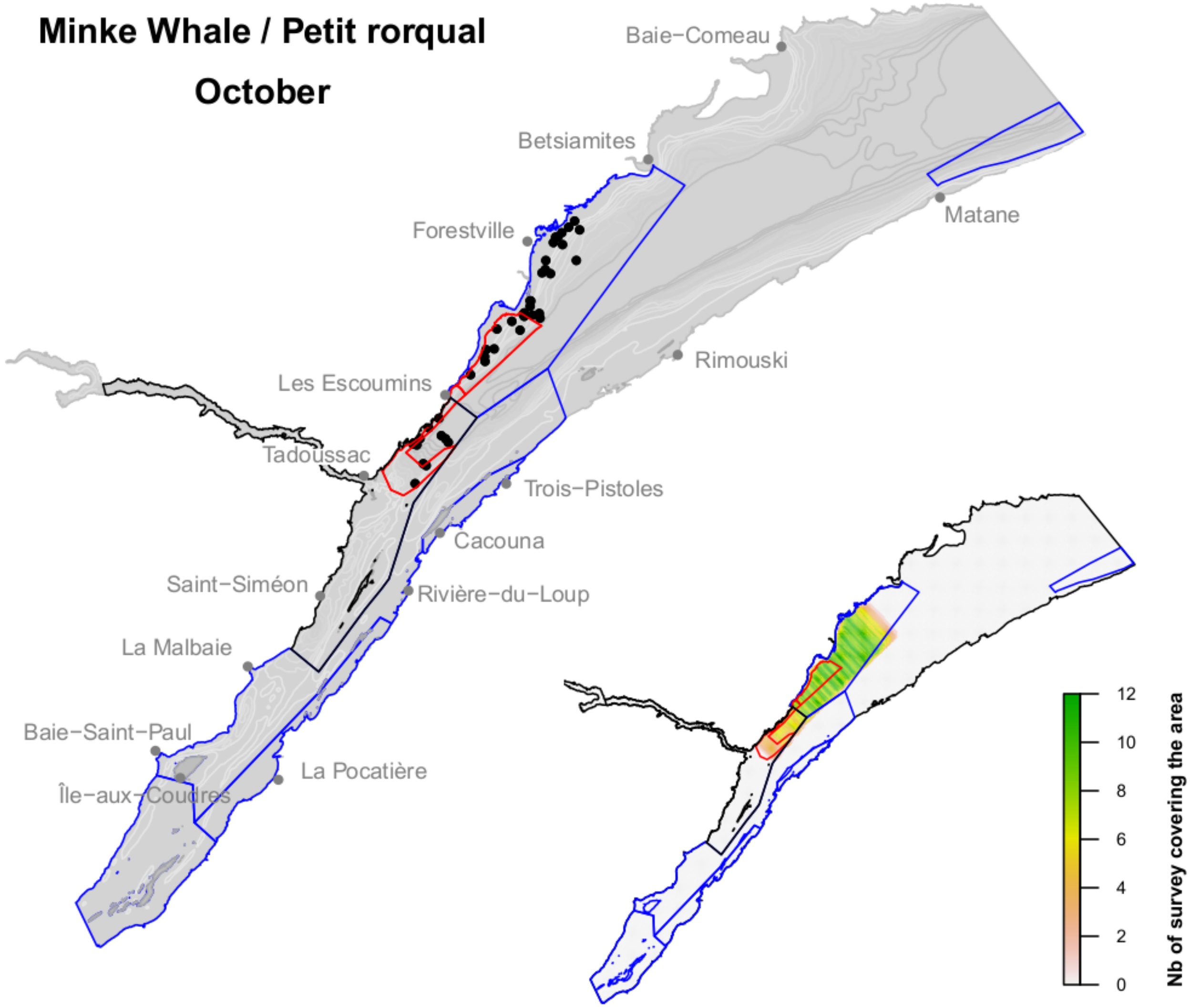

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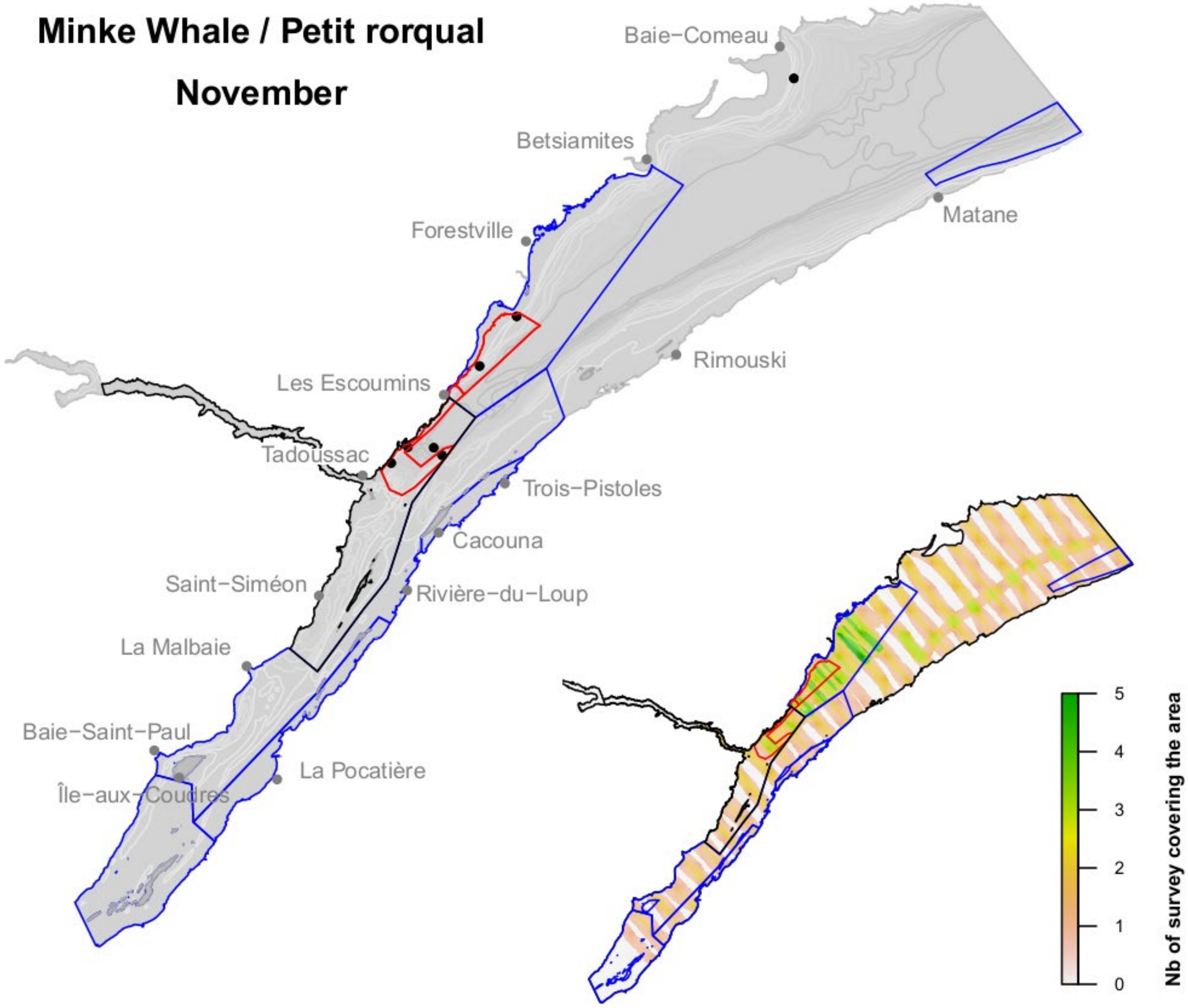

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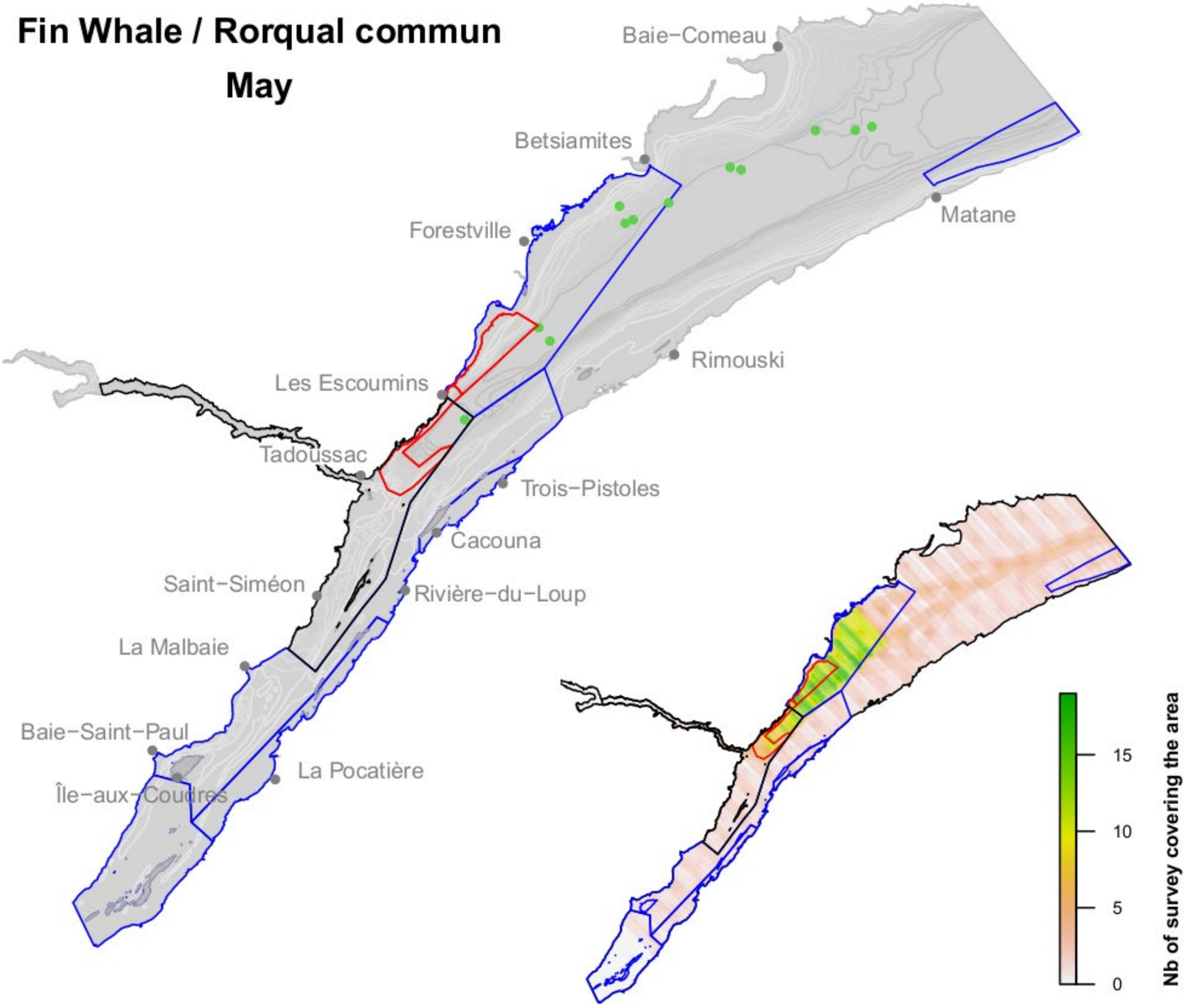
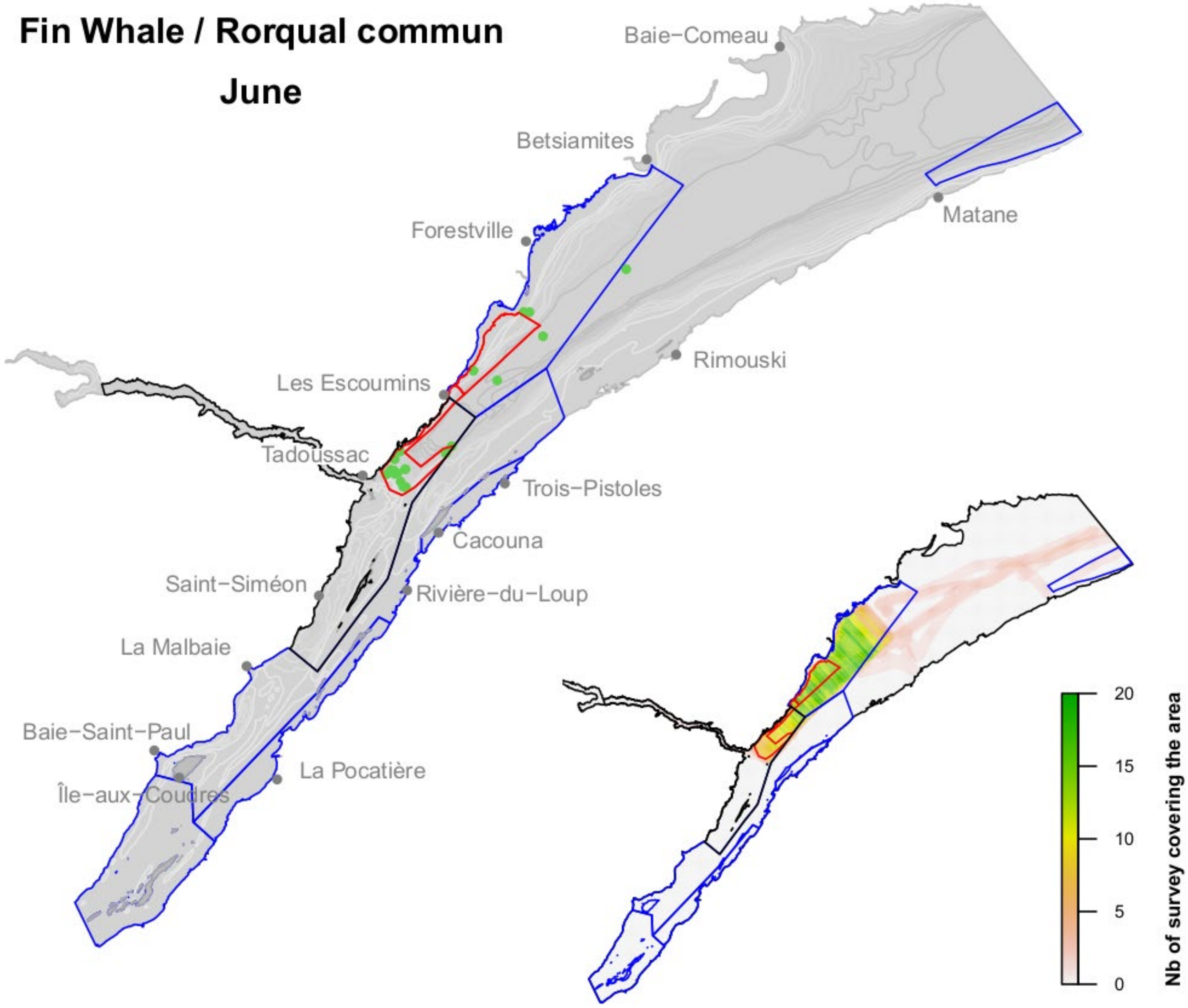


Appendix 2. Monthly distribution of fin whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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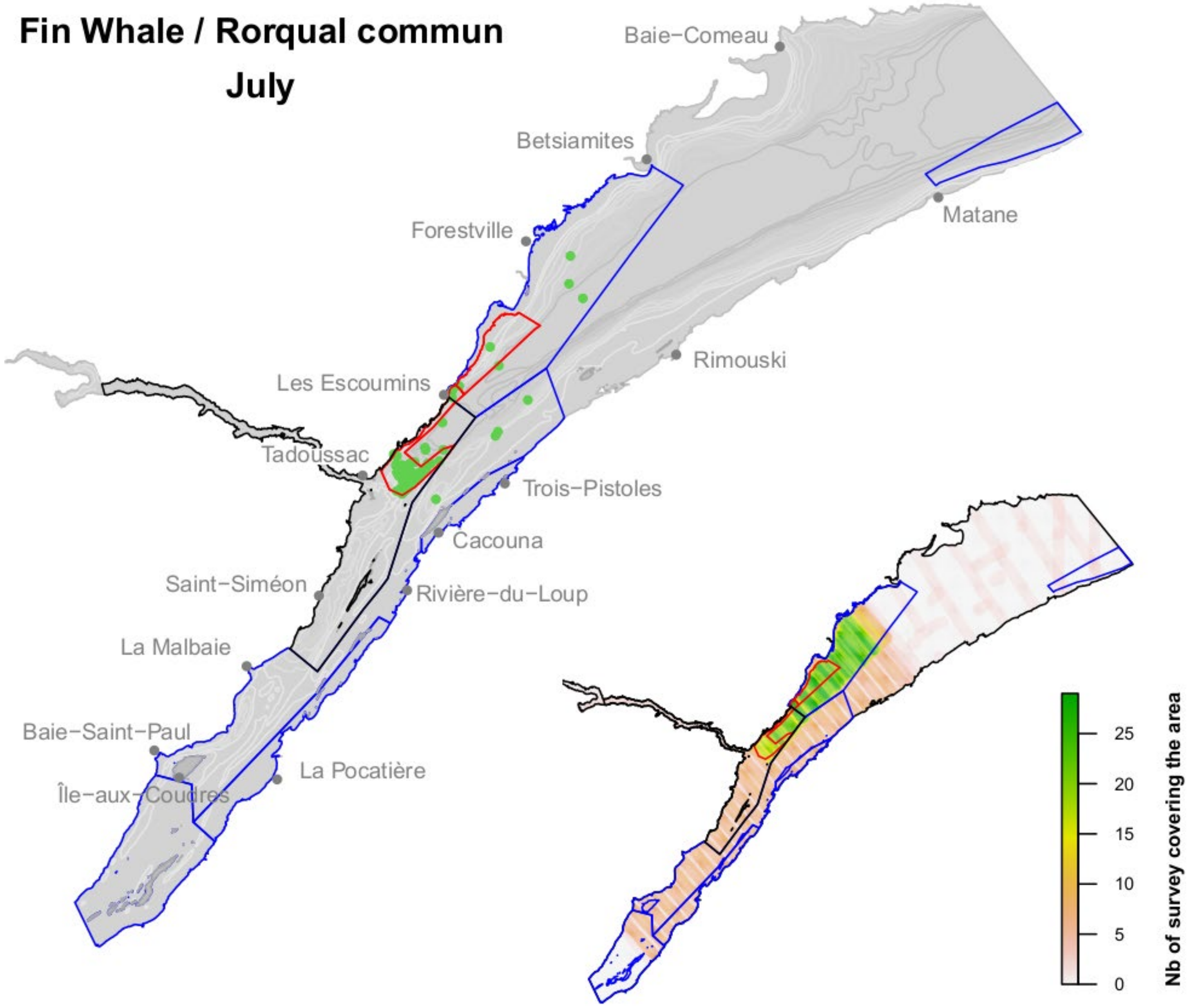

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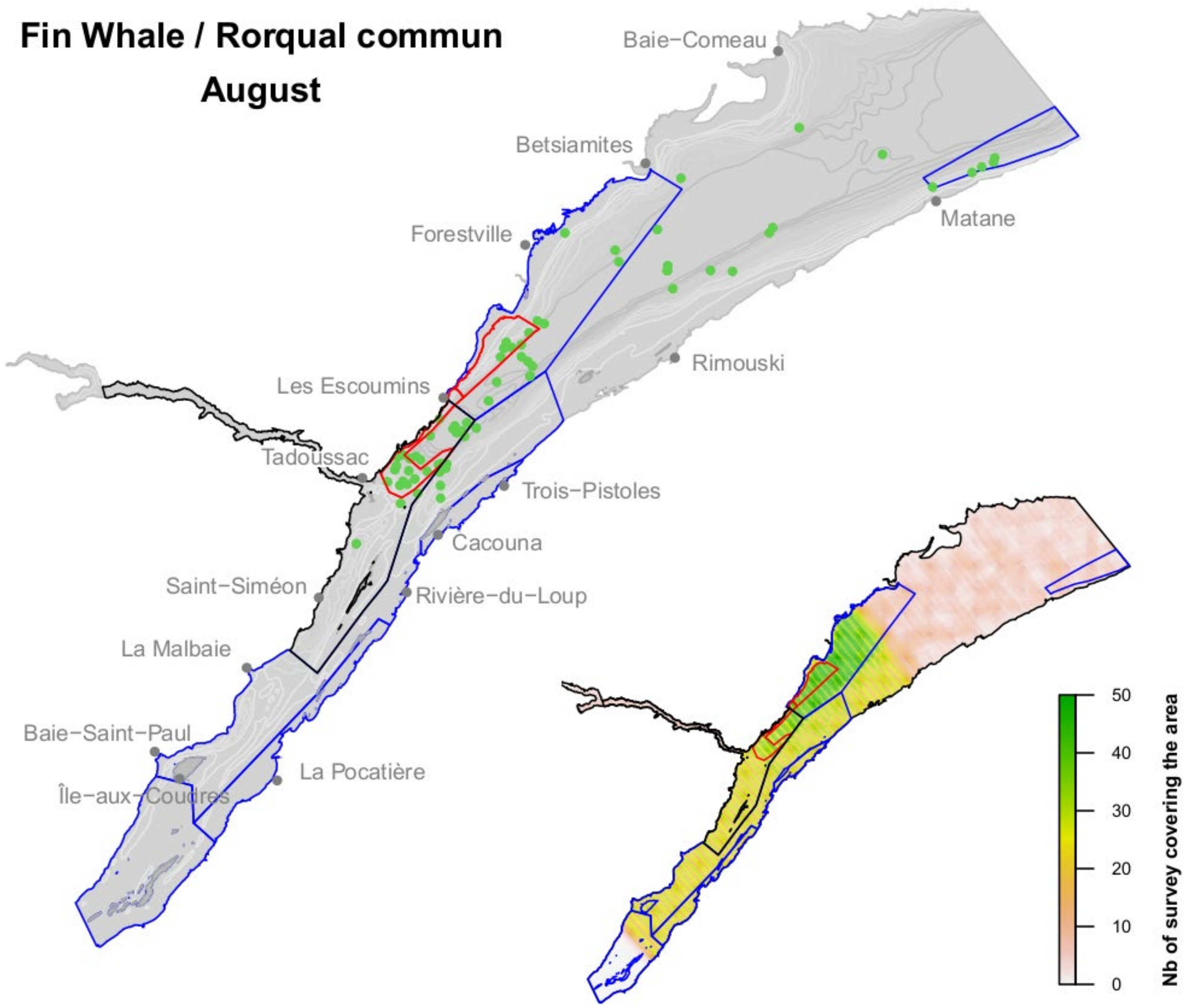

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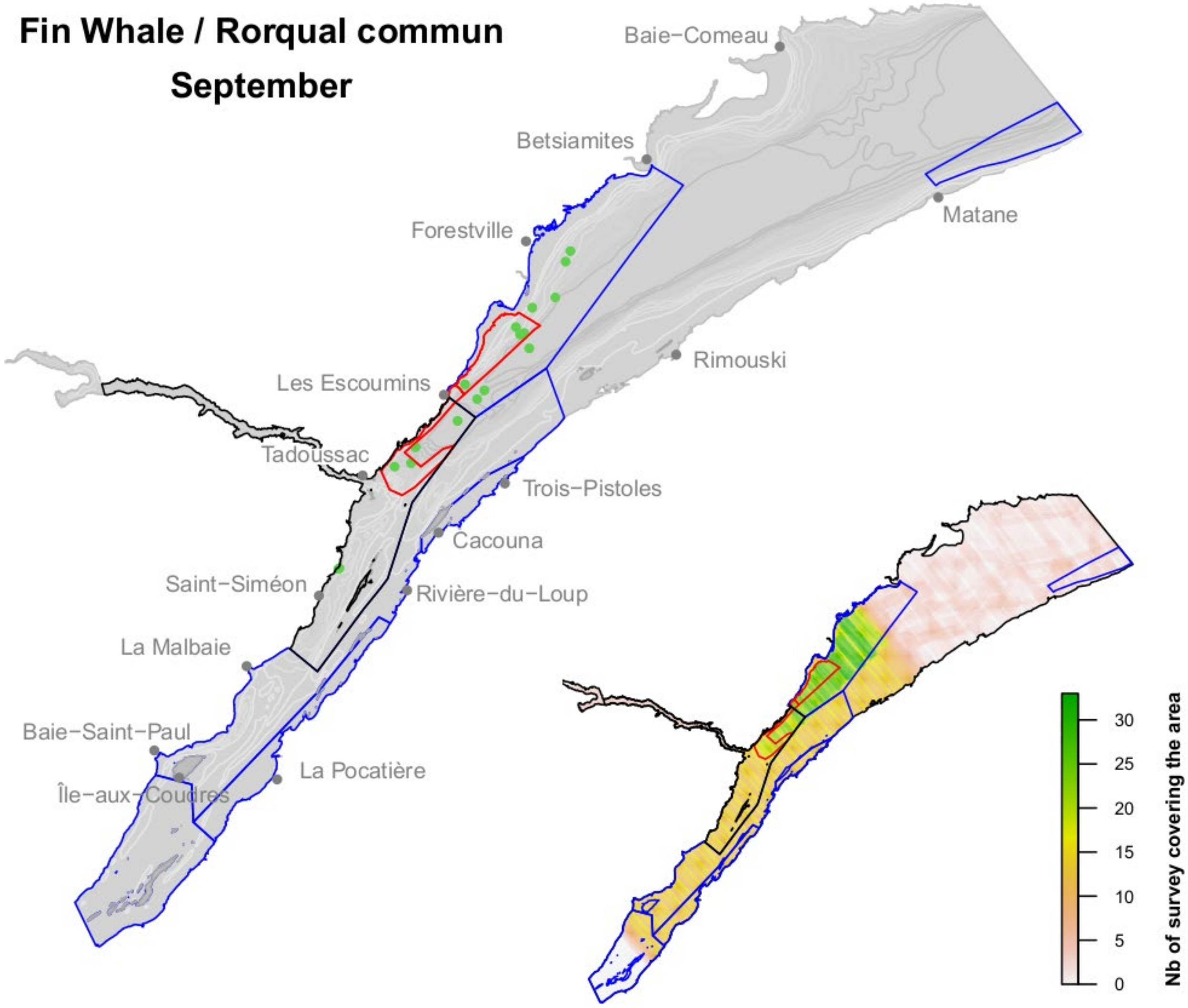

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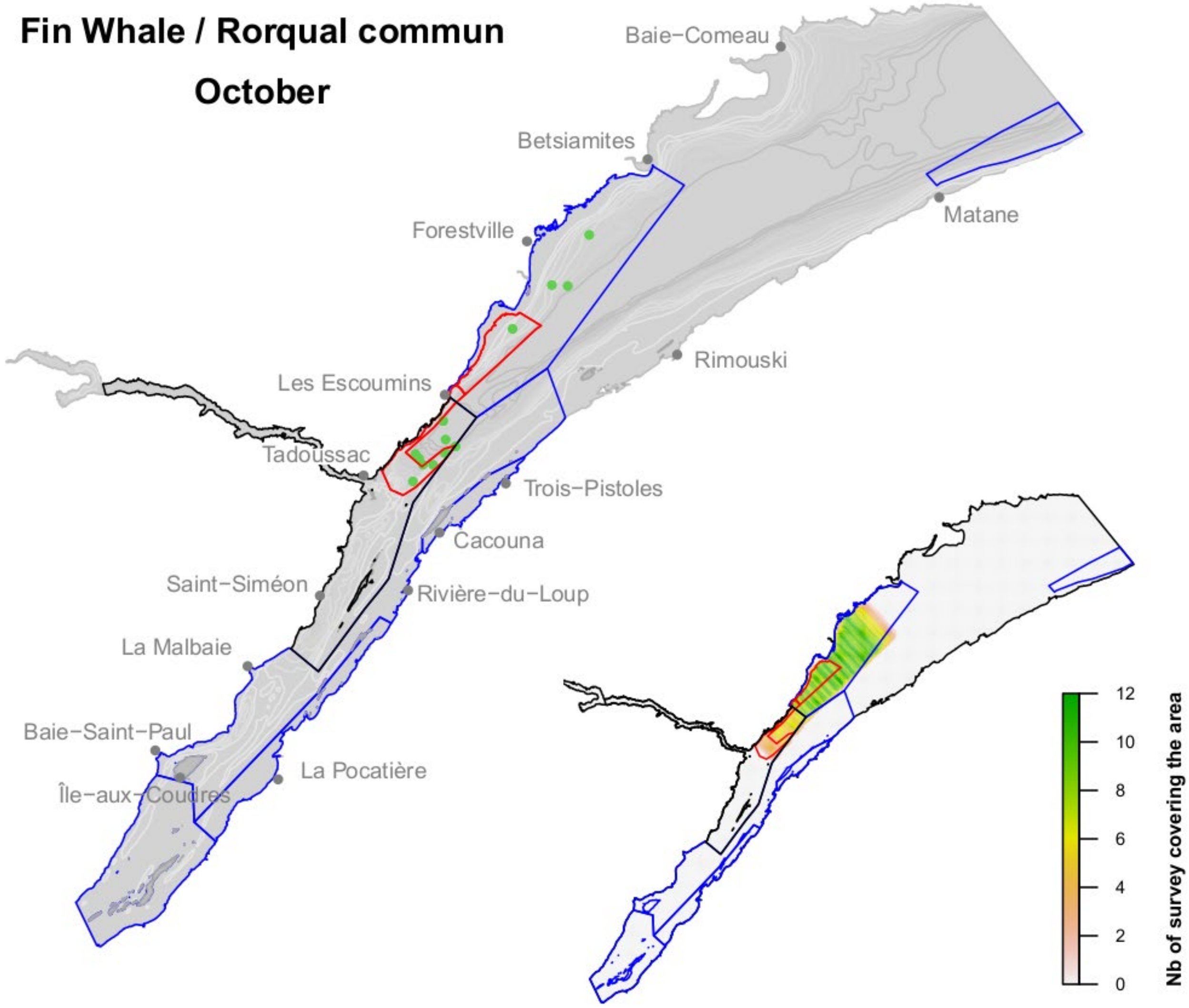

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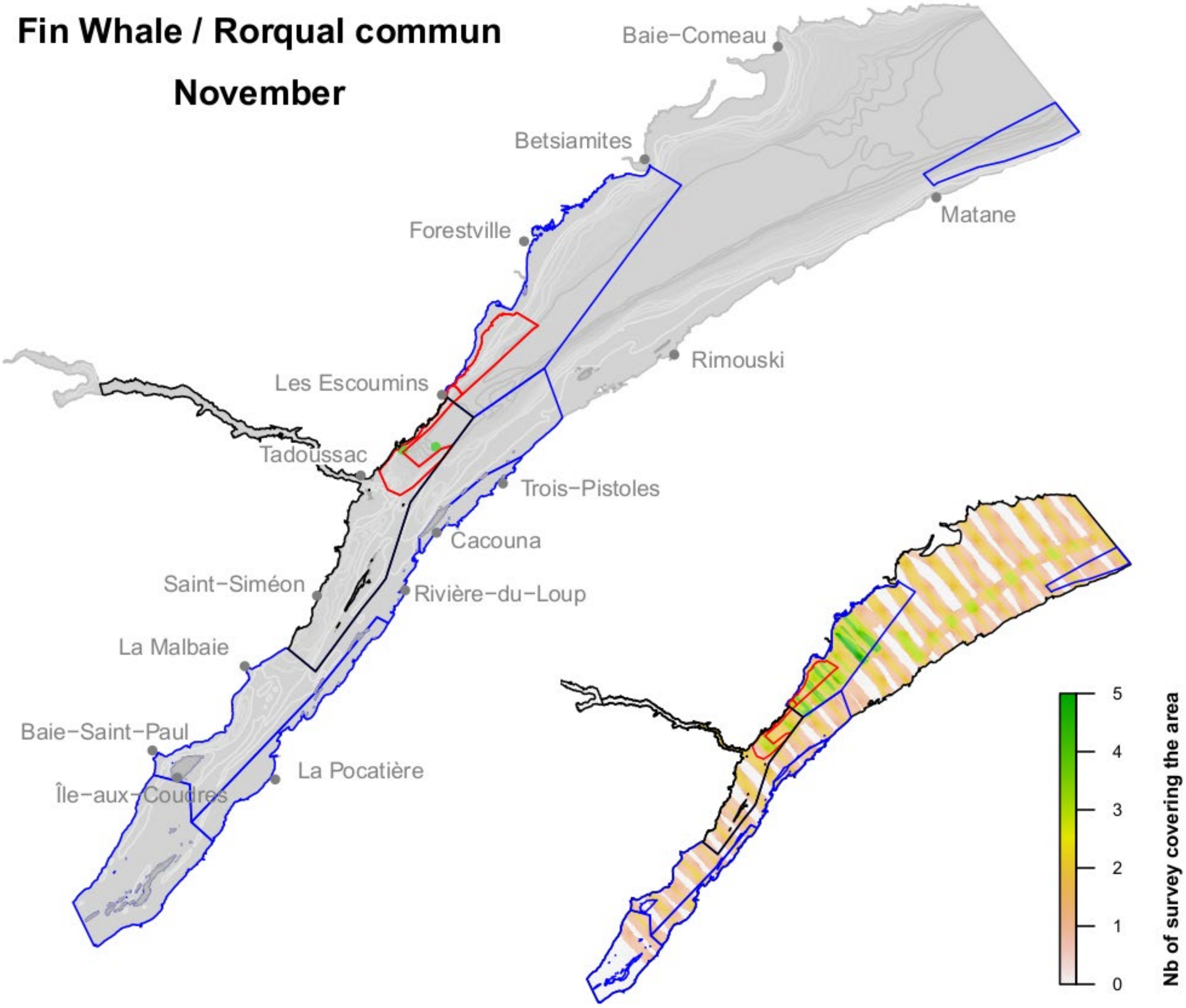

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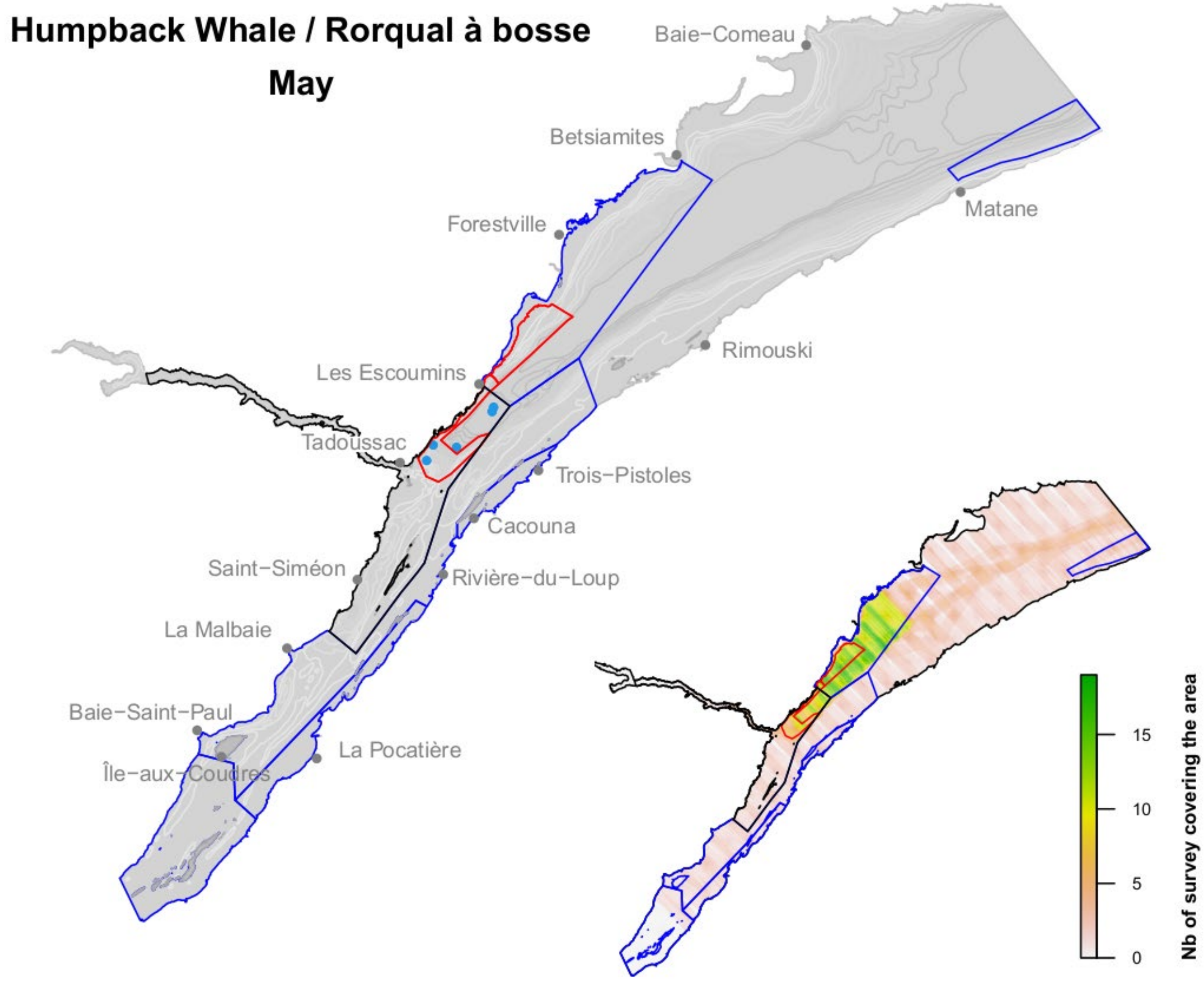
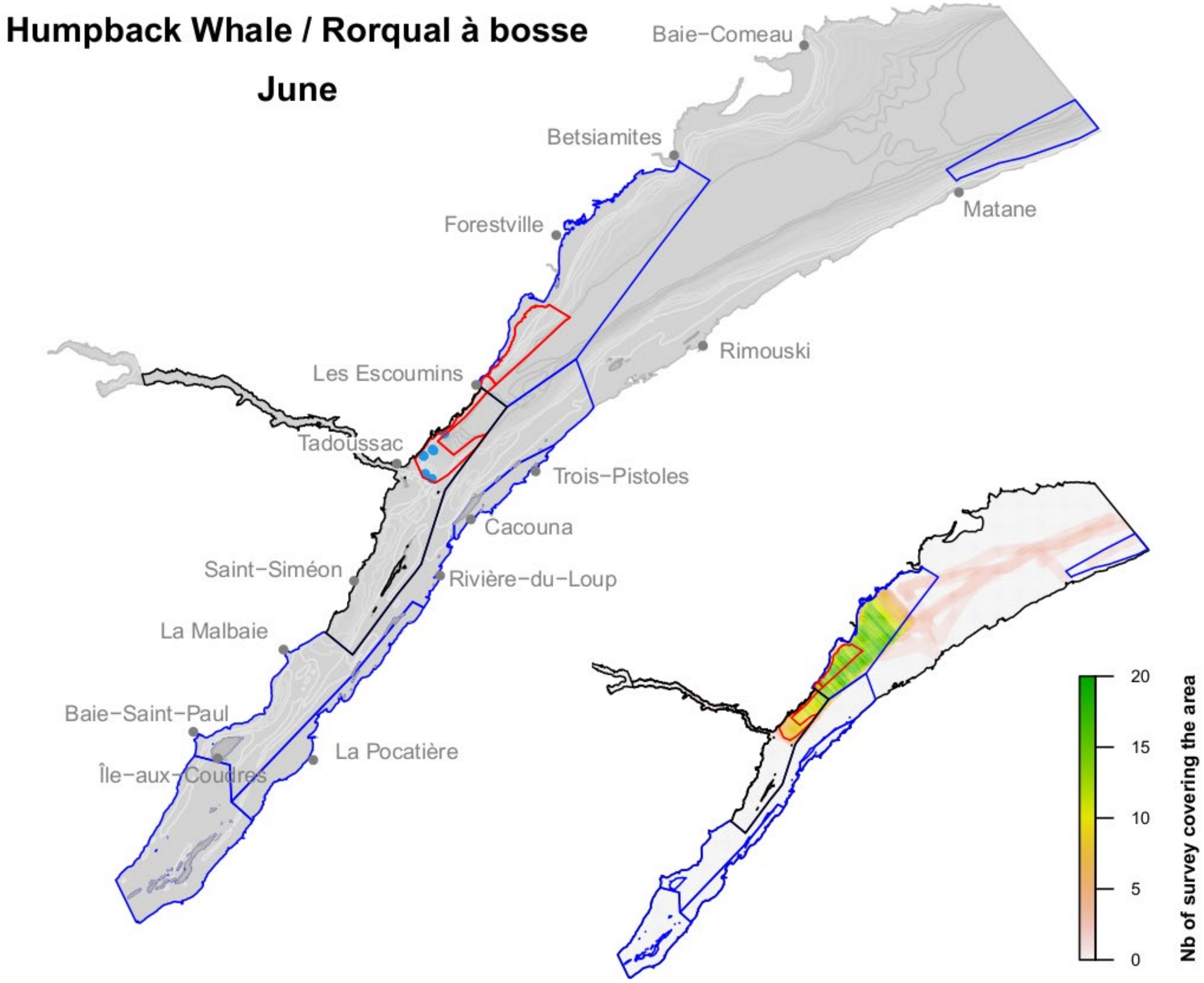


Appendix 3. Monthly distribution of humpback whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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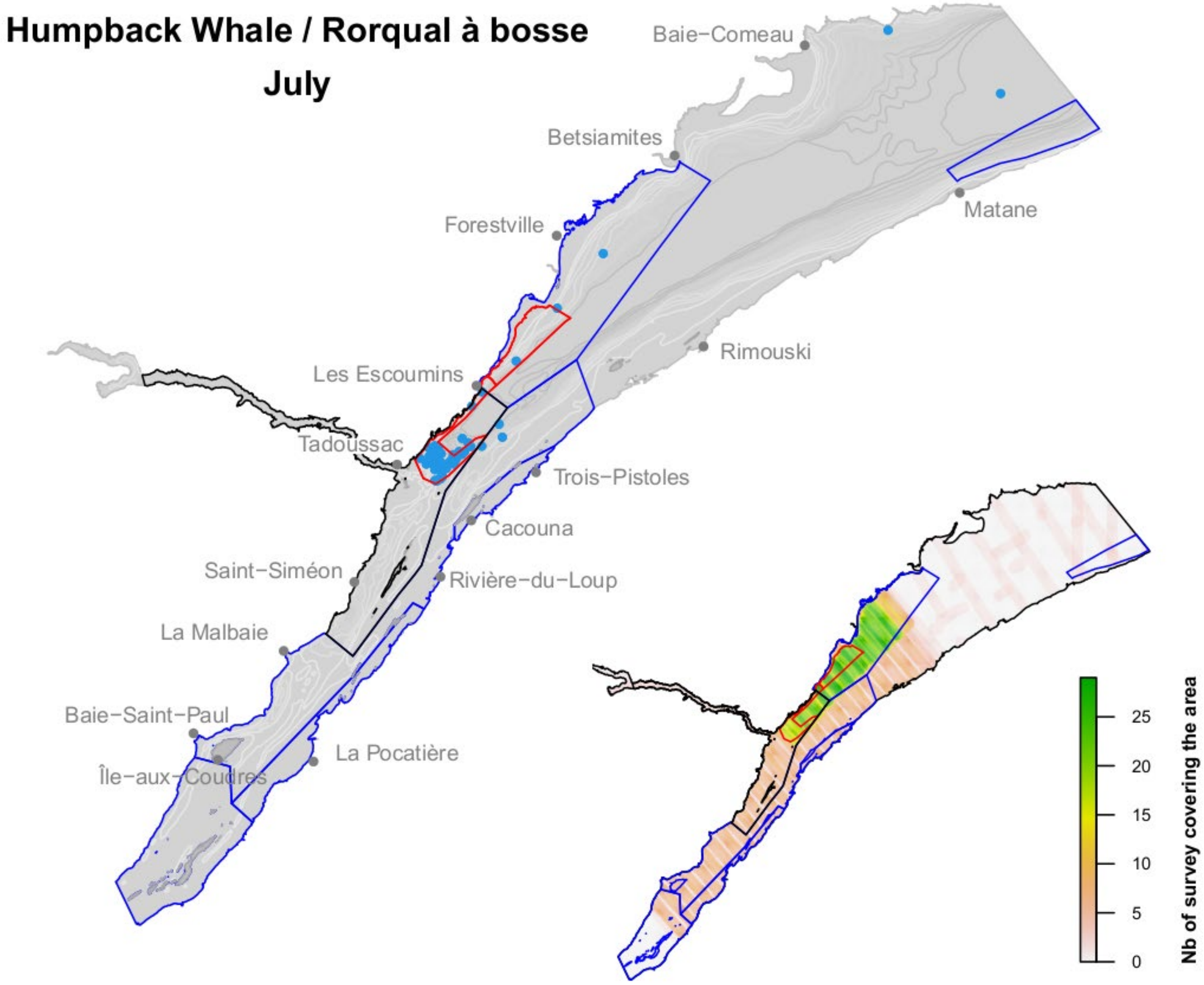

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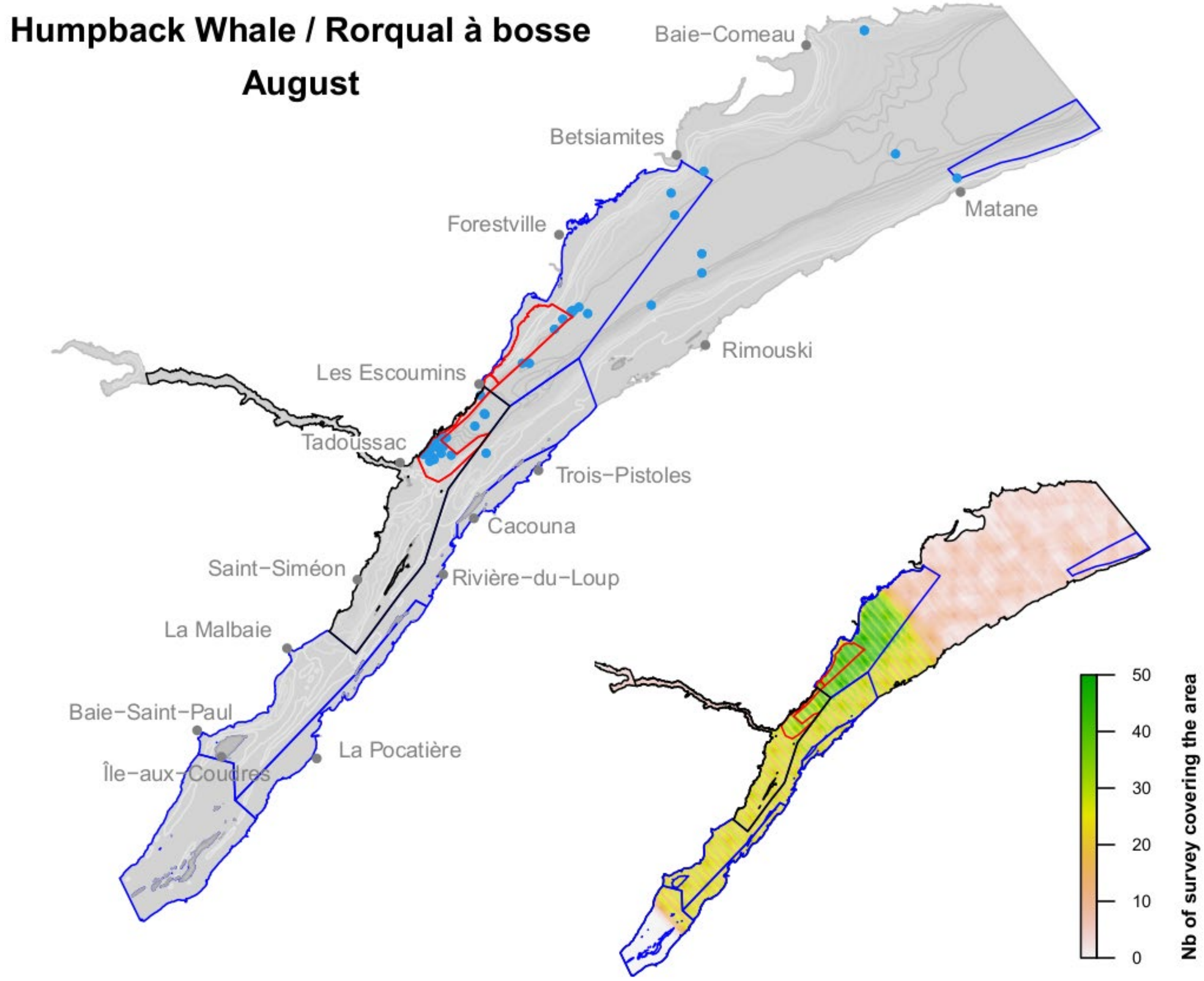

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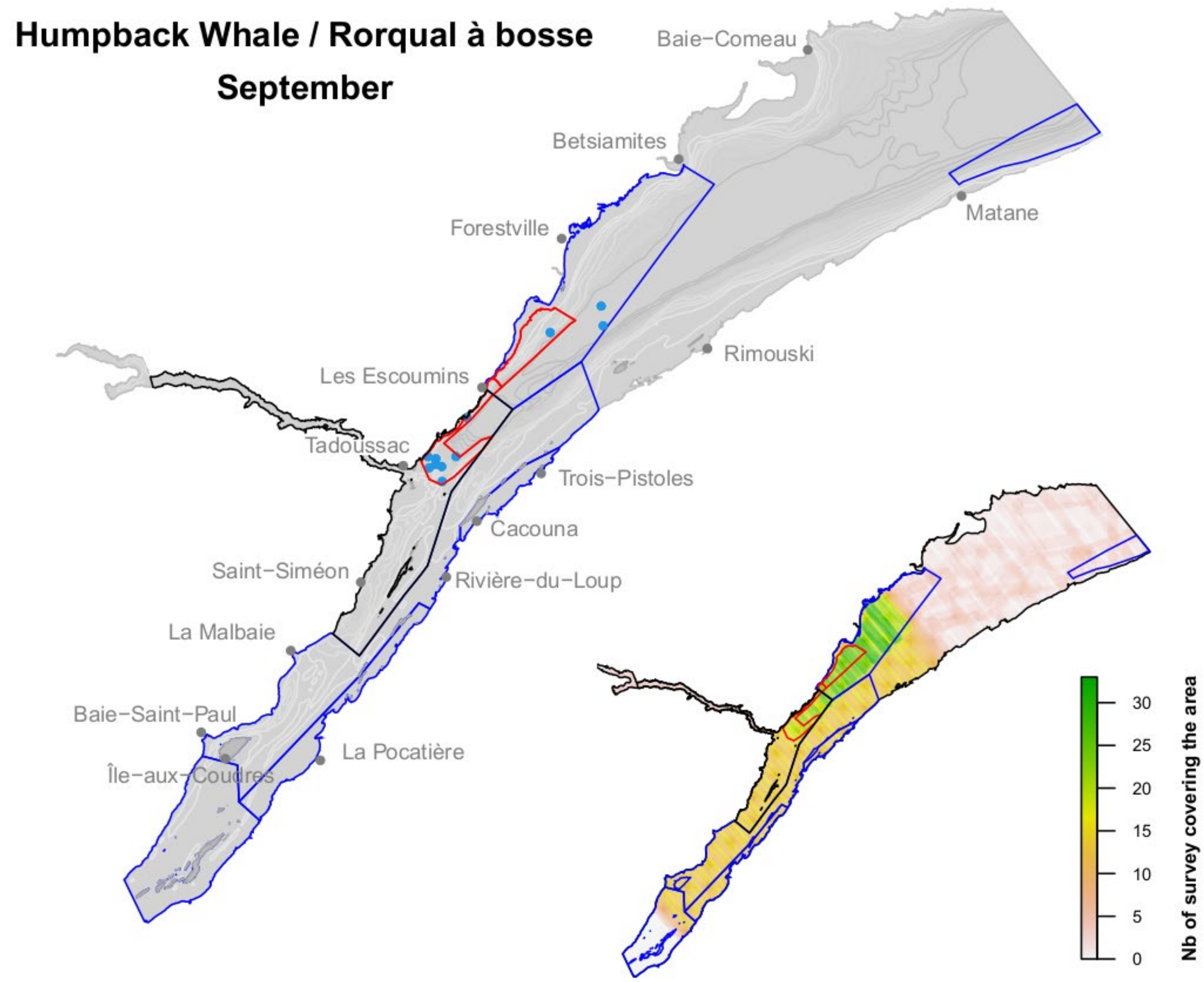

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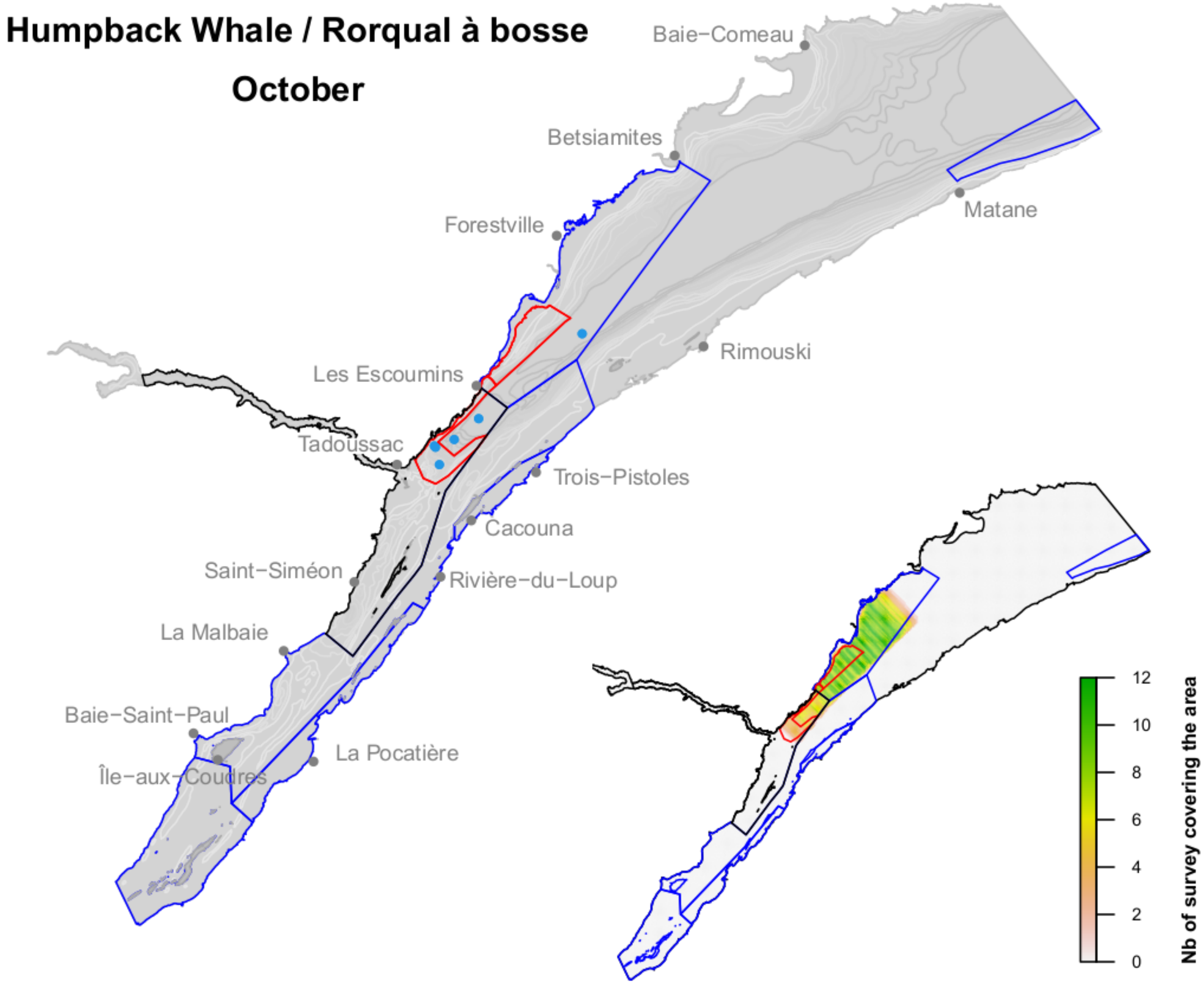

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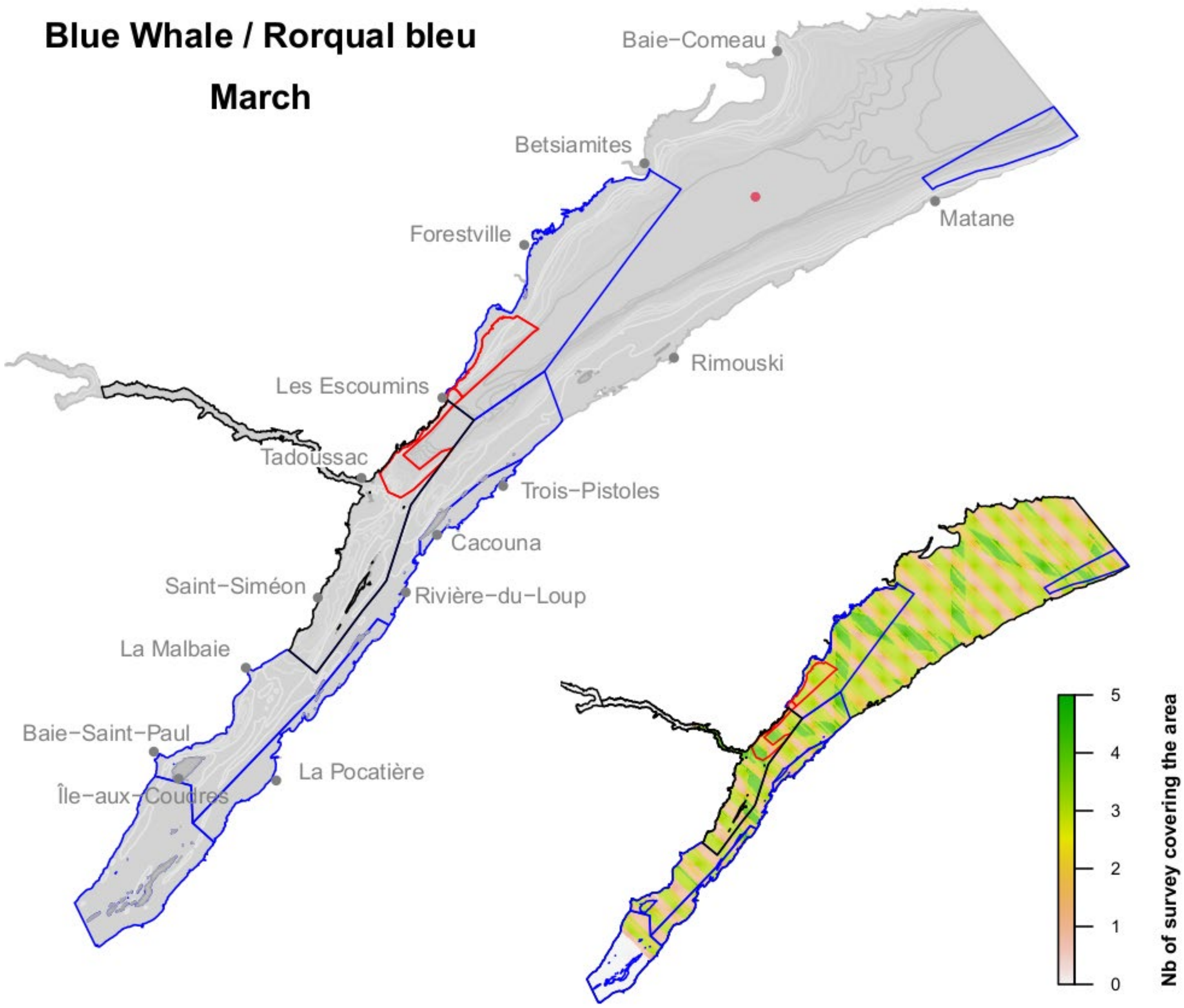
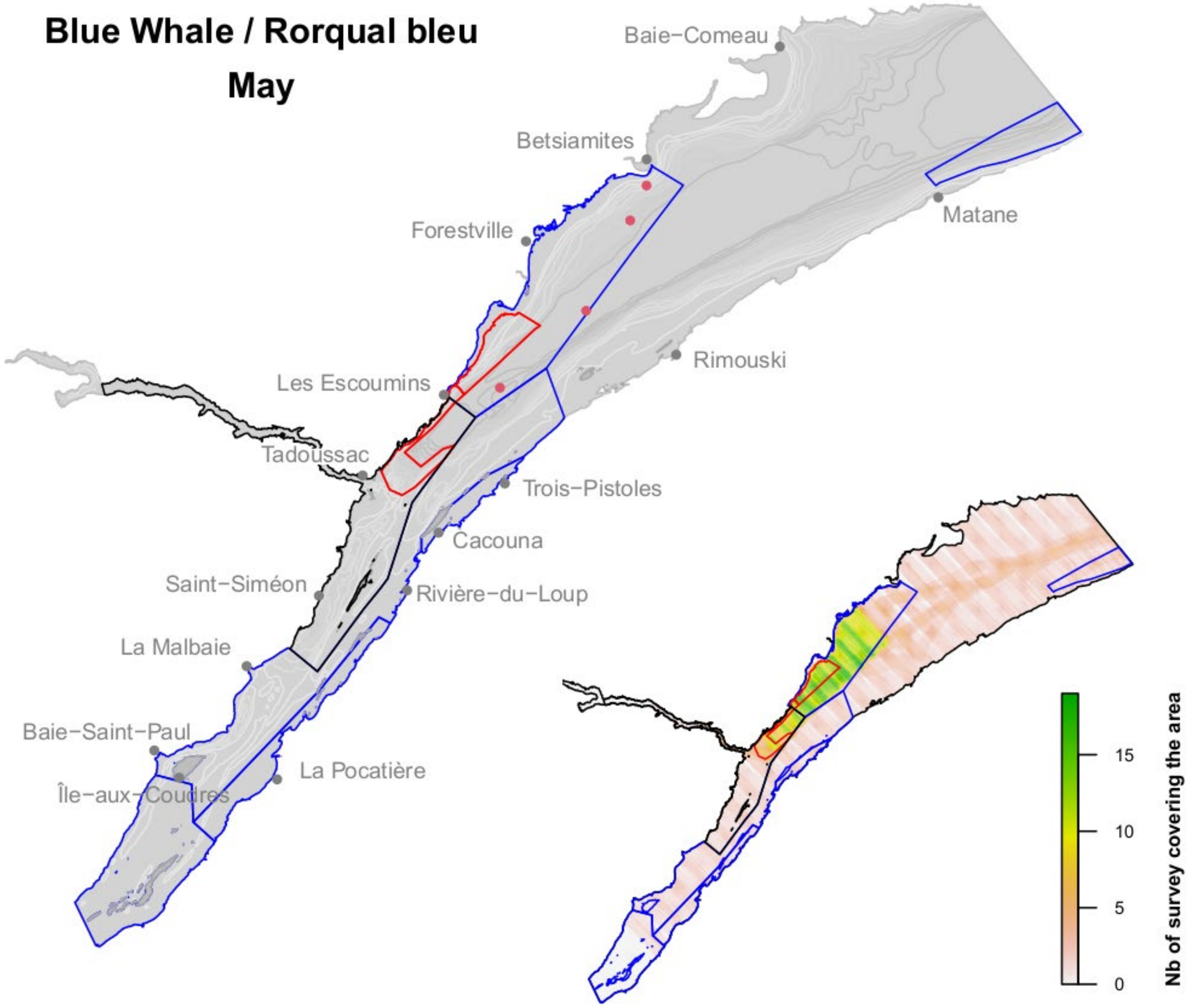


Appendix 4. Monthly distribution of blue whale observations and observation effort in the St. Lawrence estuary based on boat and aerial surveys conducted between 1995 and 2017. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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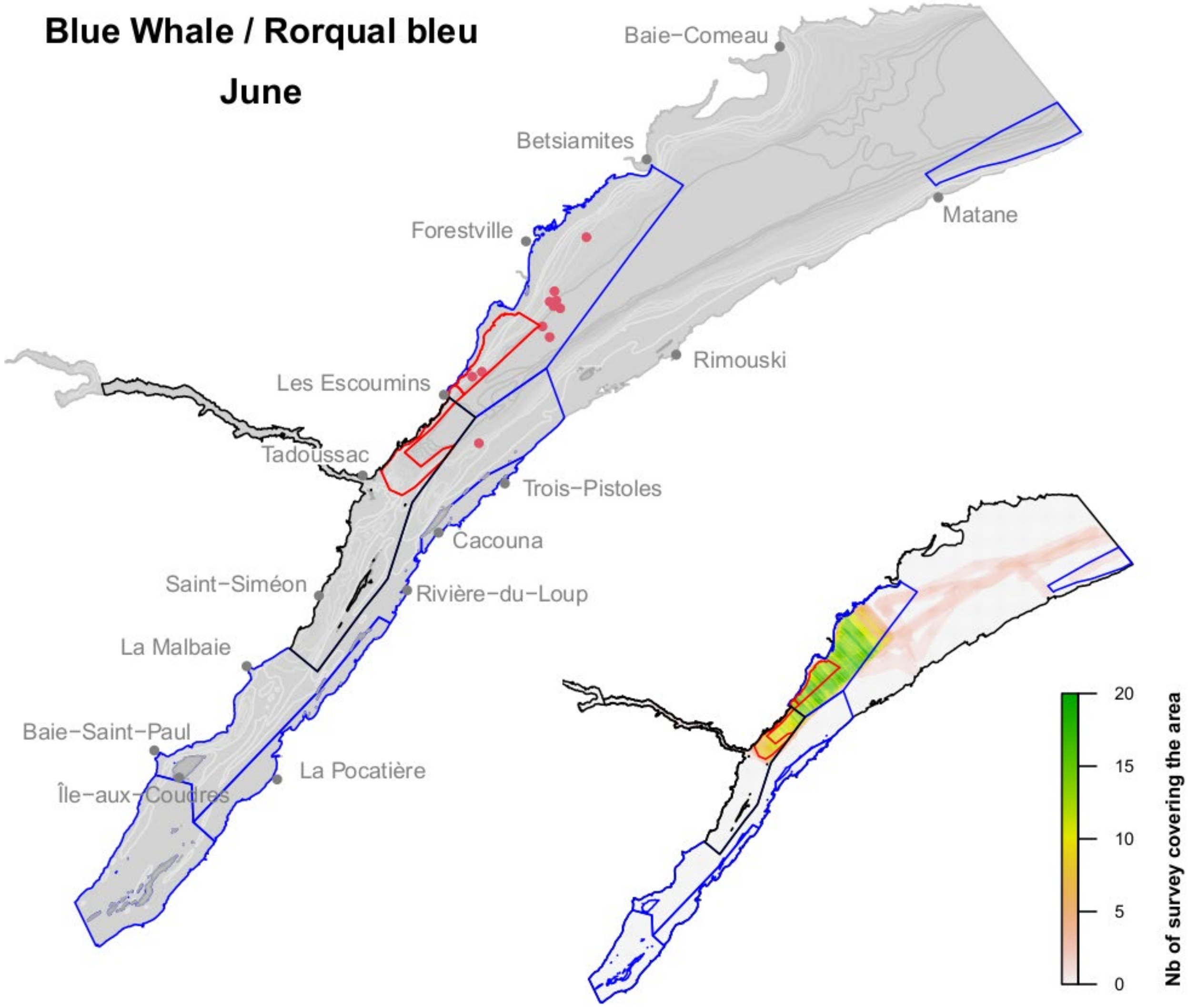

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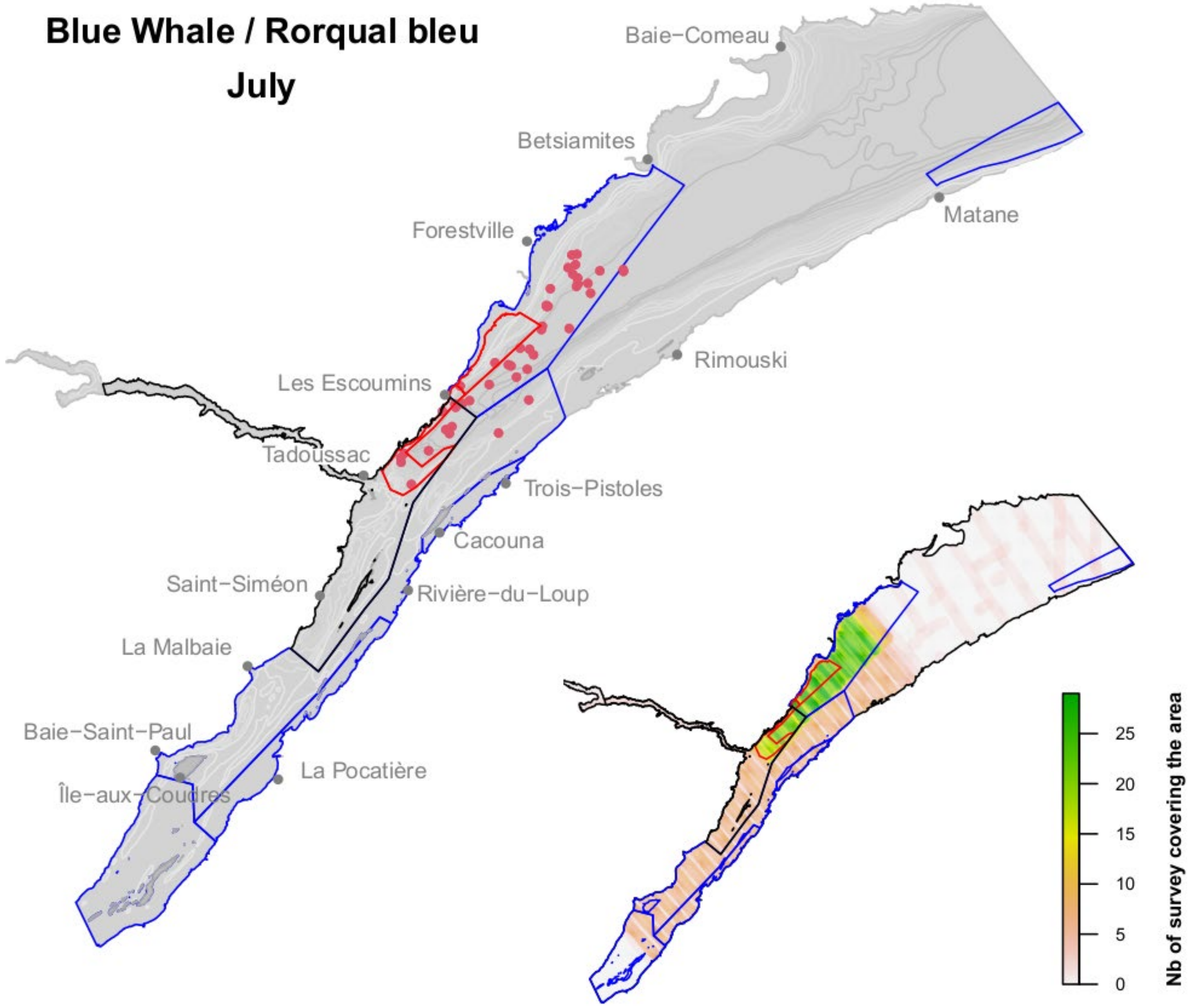

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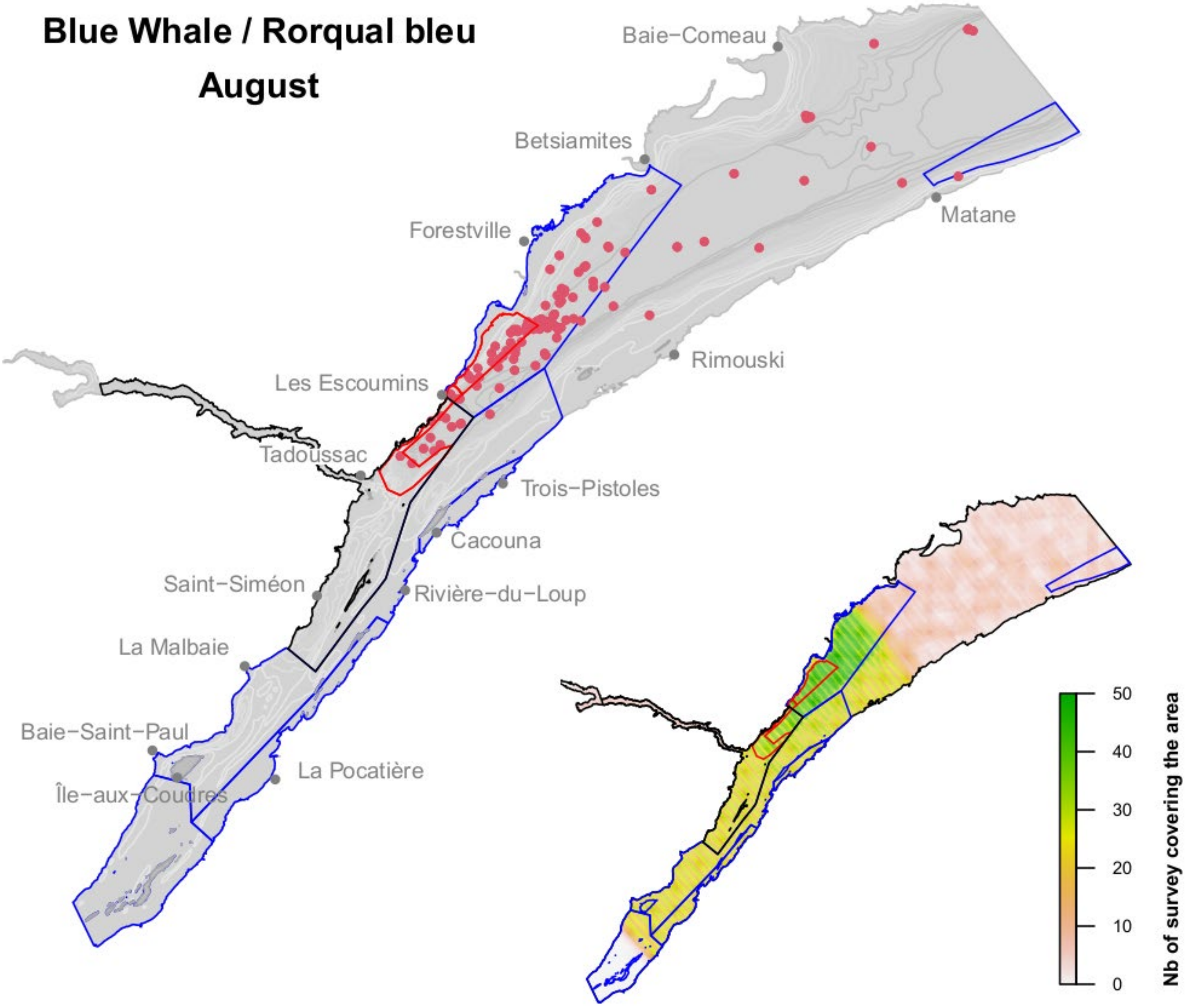

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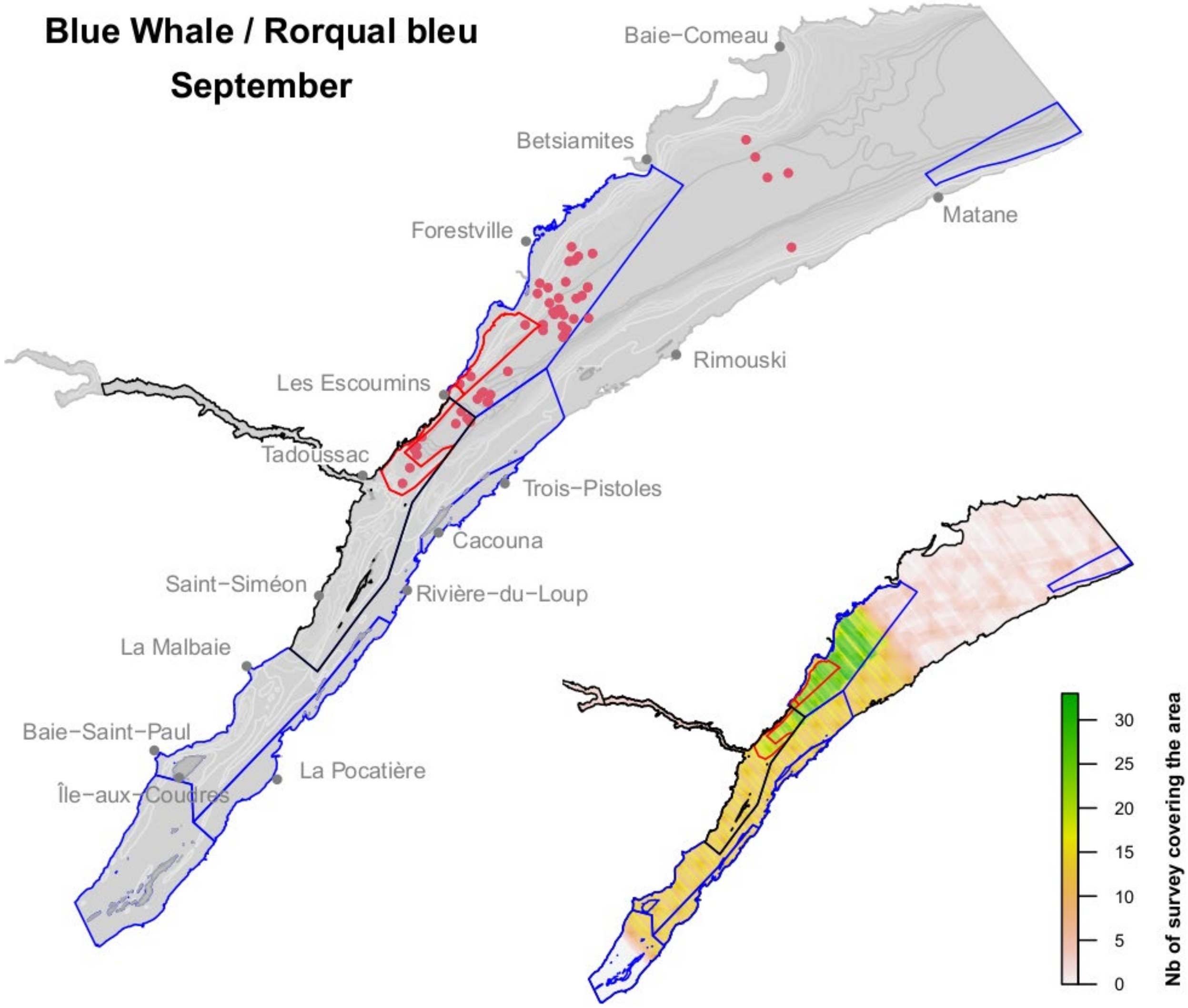

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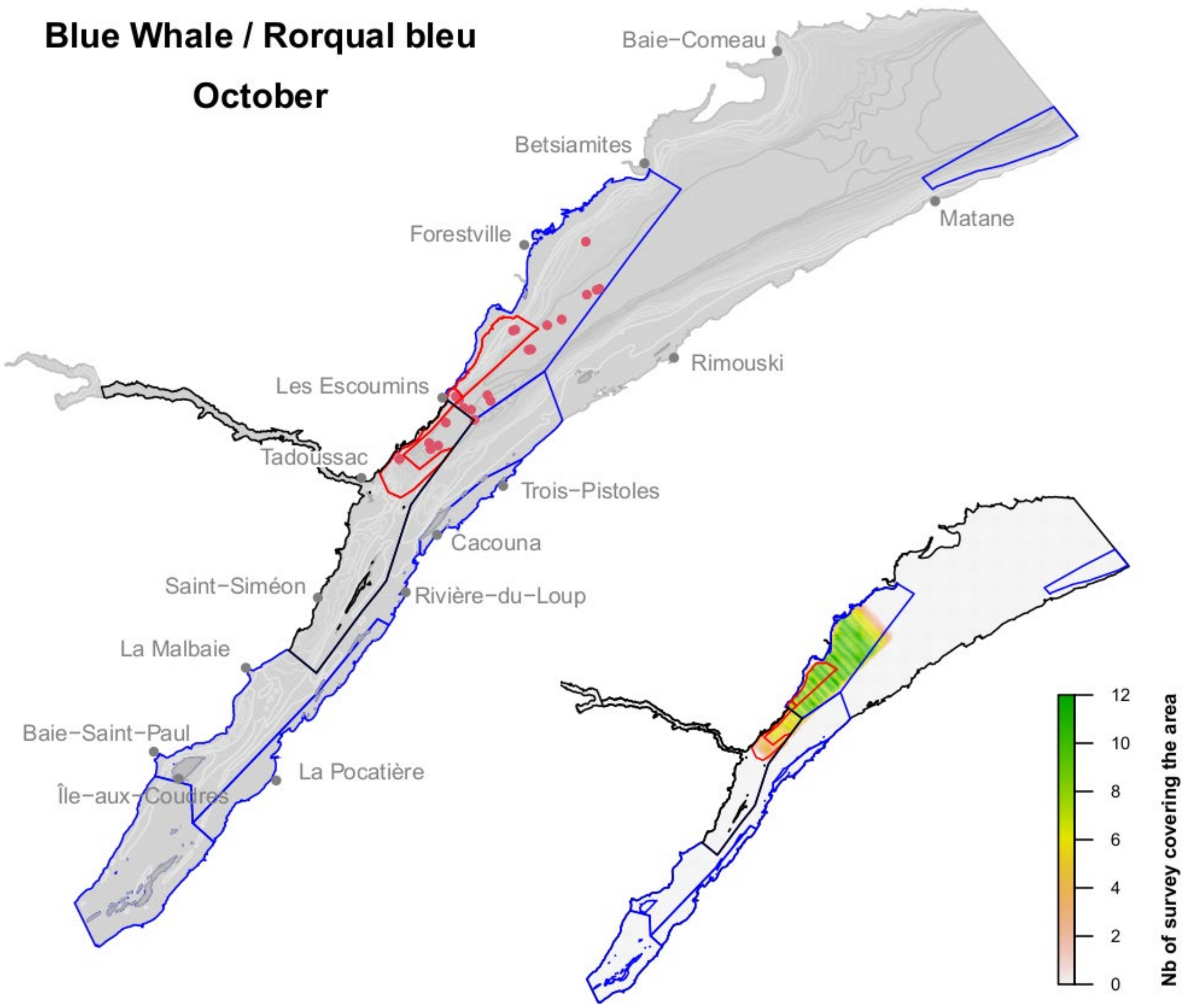

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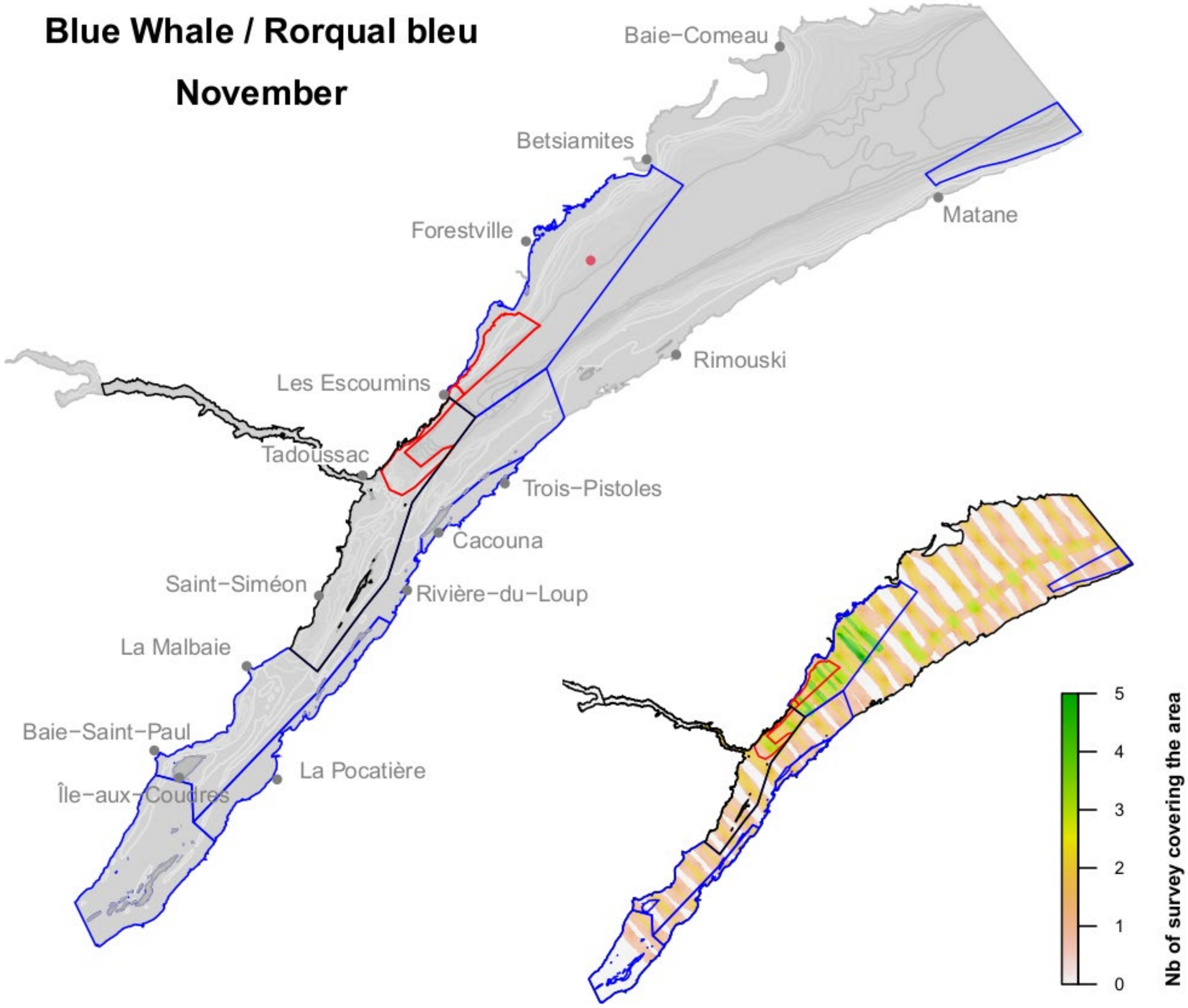

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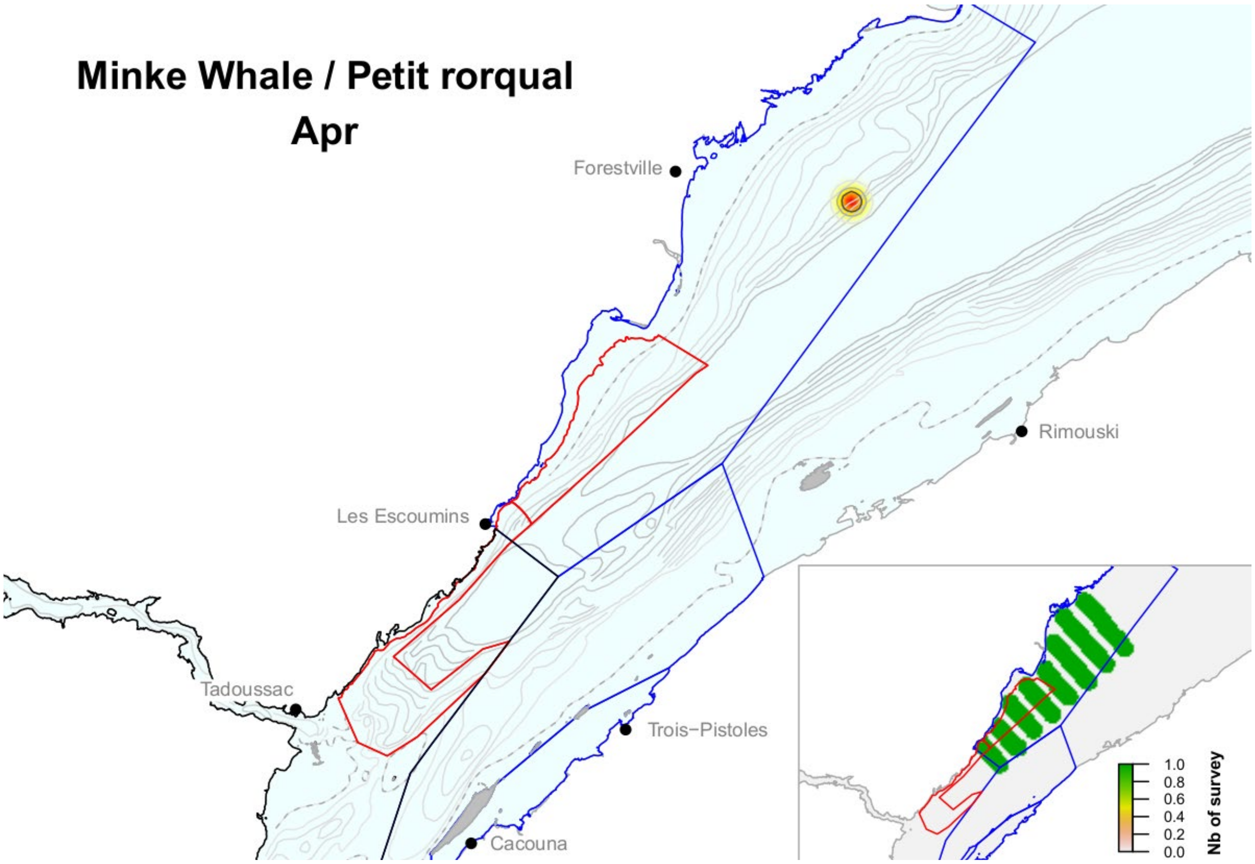
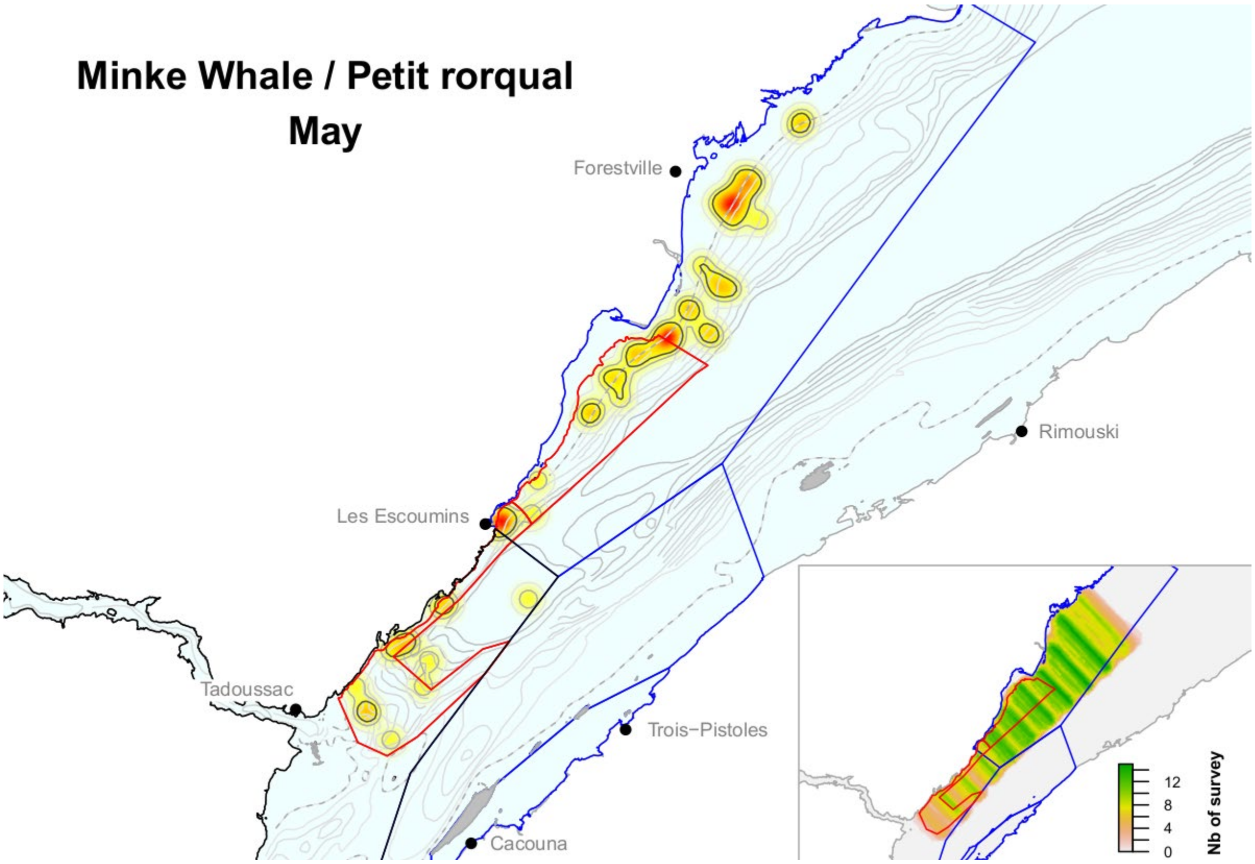


Appendix 5. Kernel representation of the monthly distribution of minke whale observations and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



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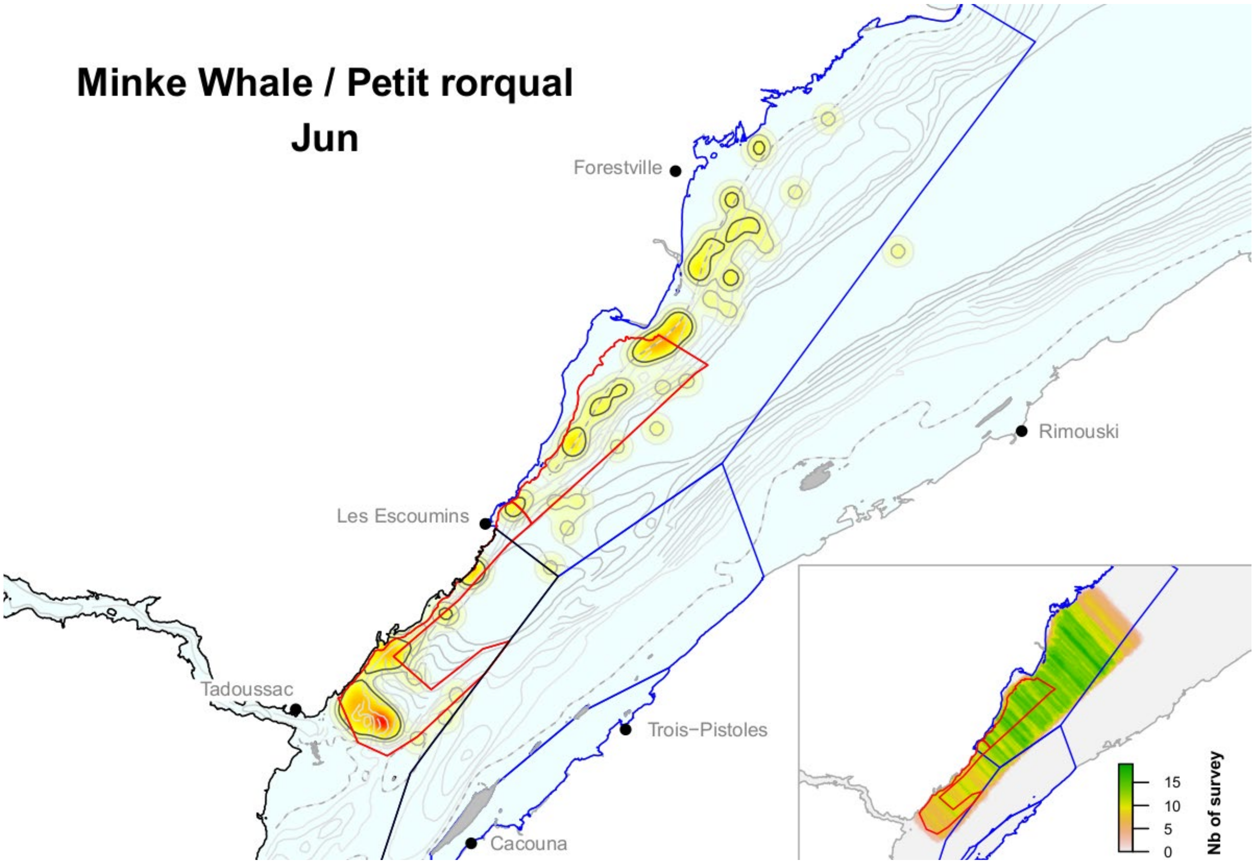

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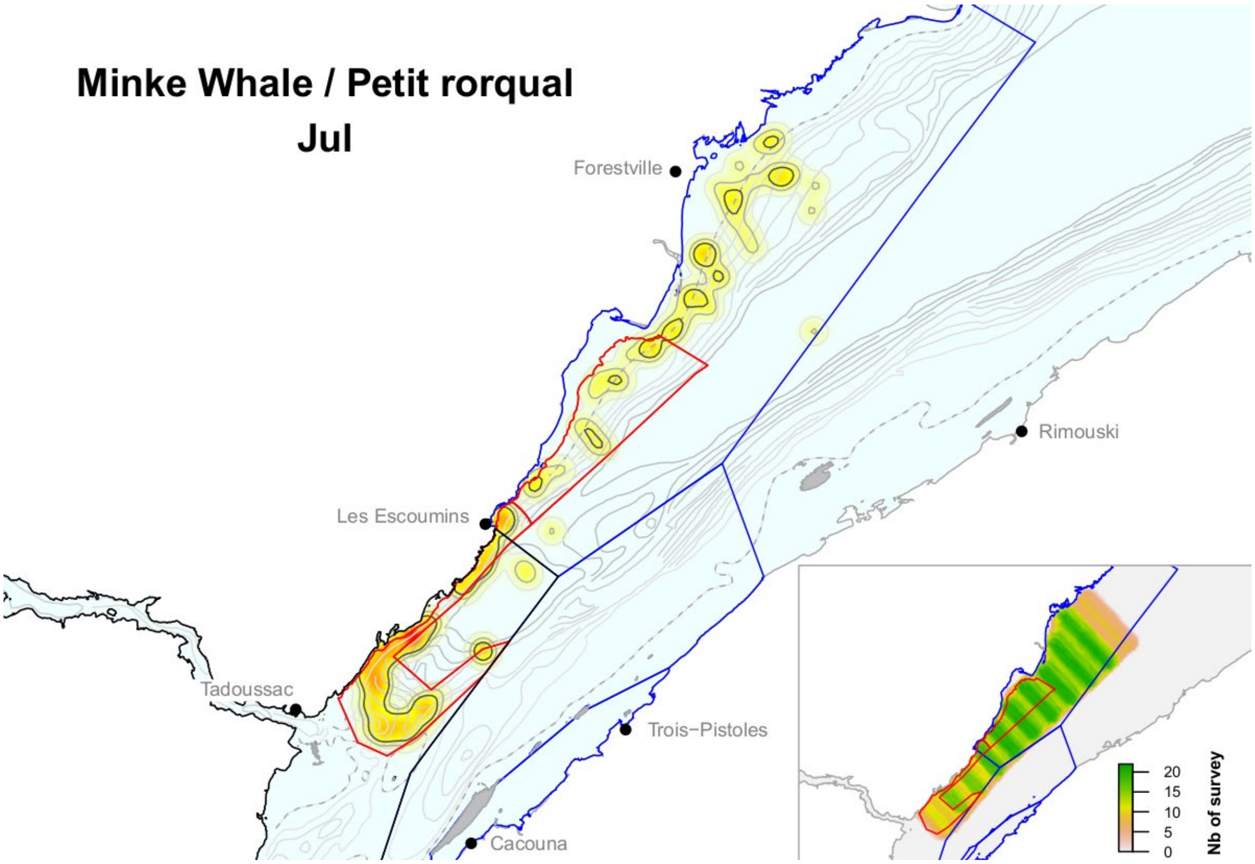

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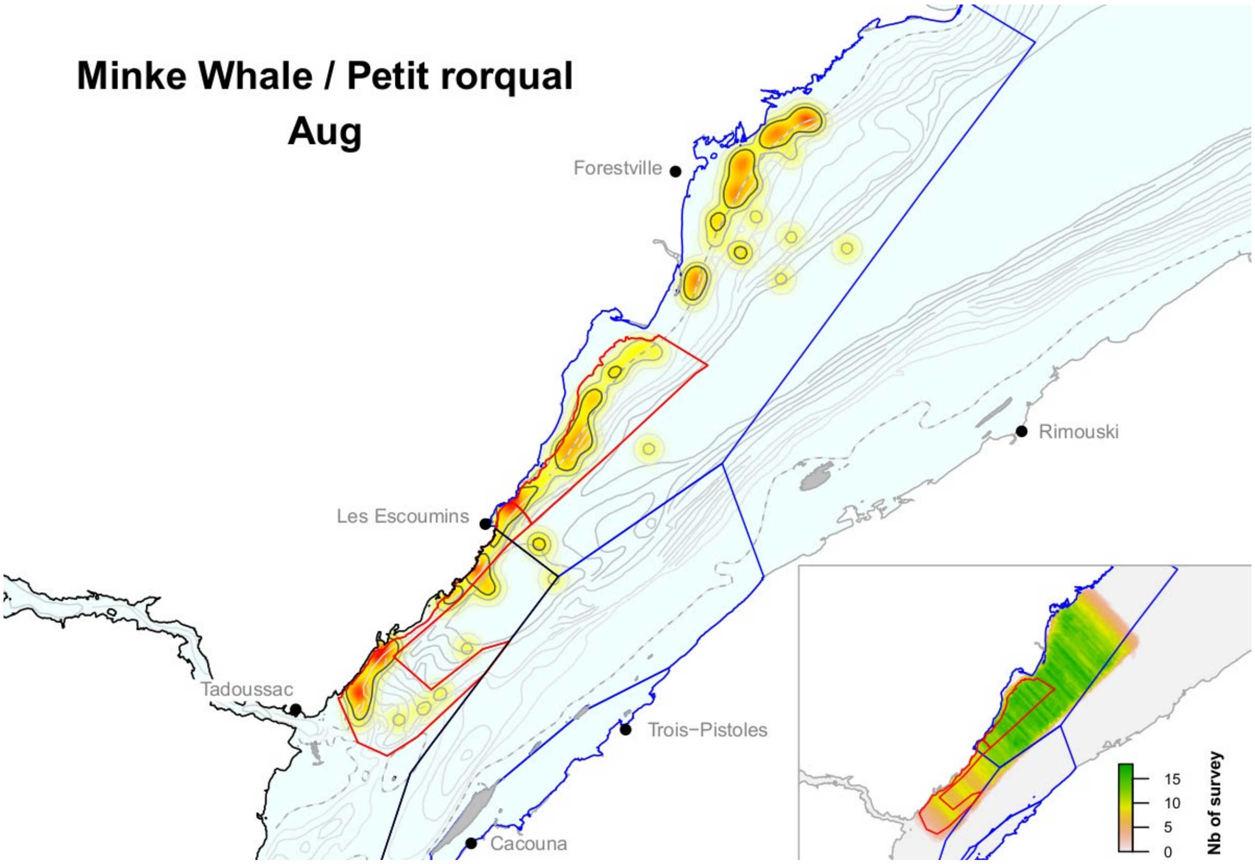

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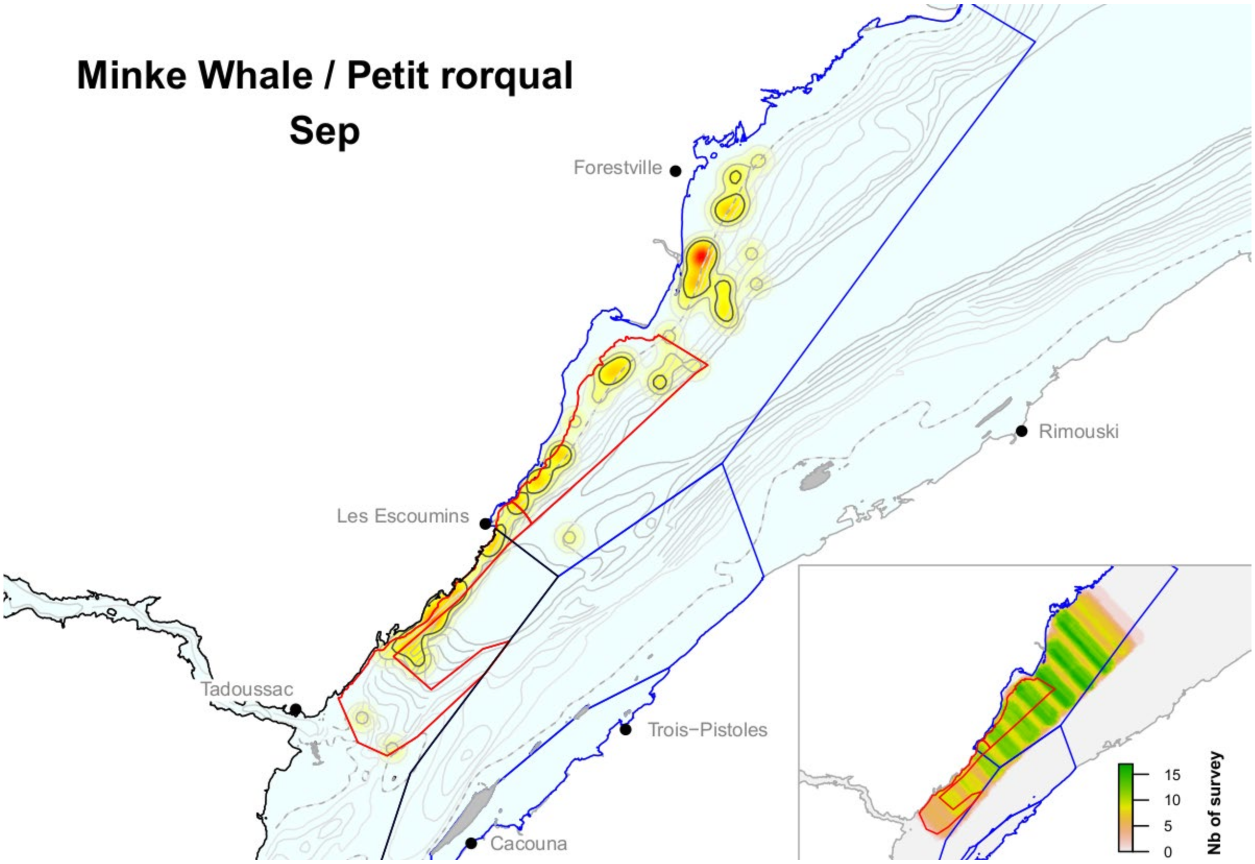

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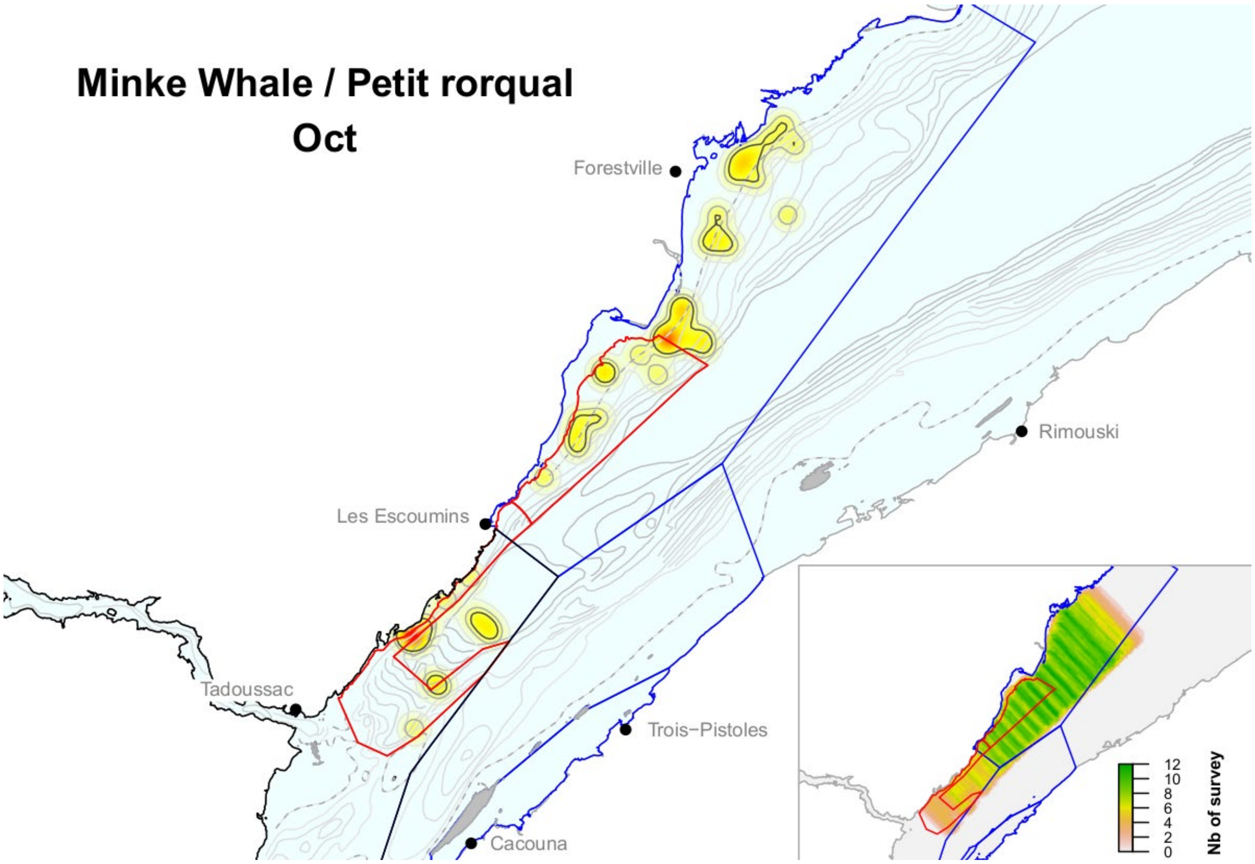

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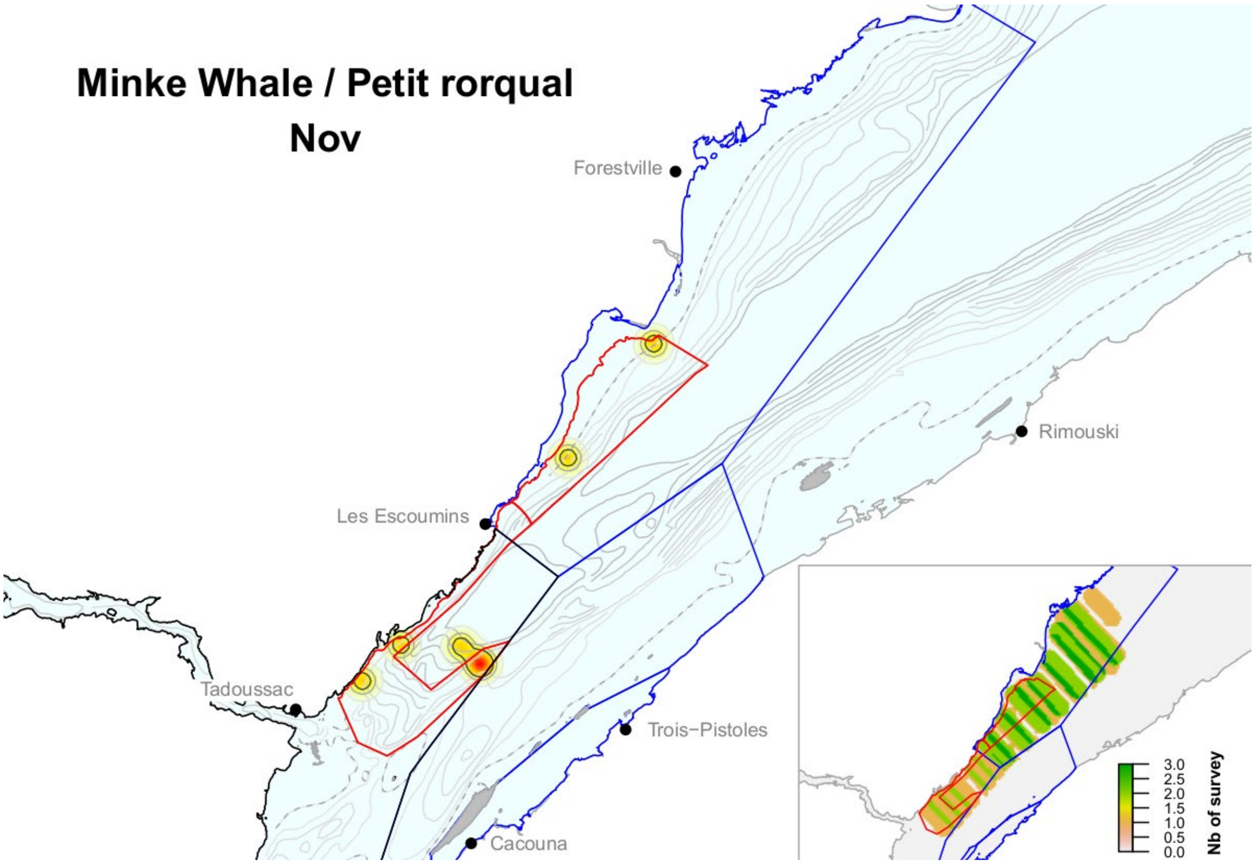

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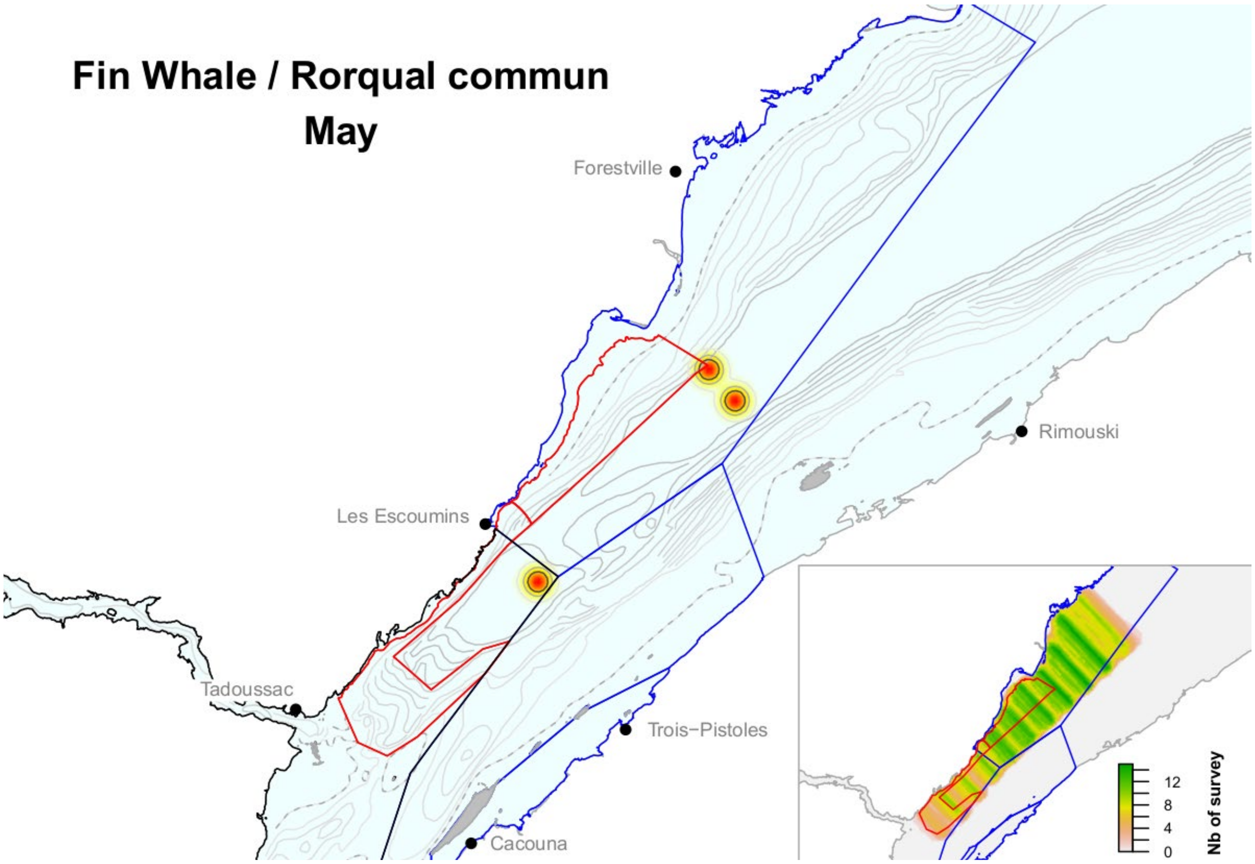
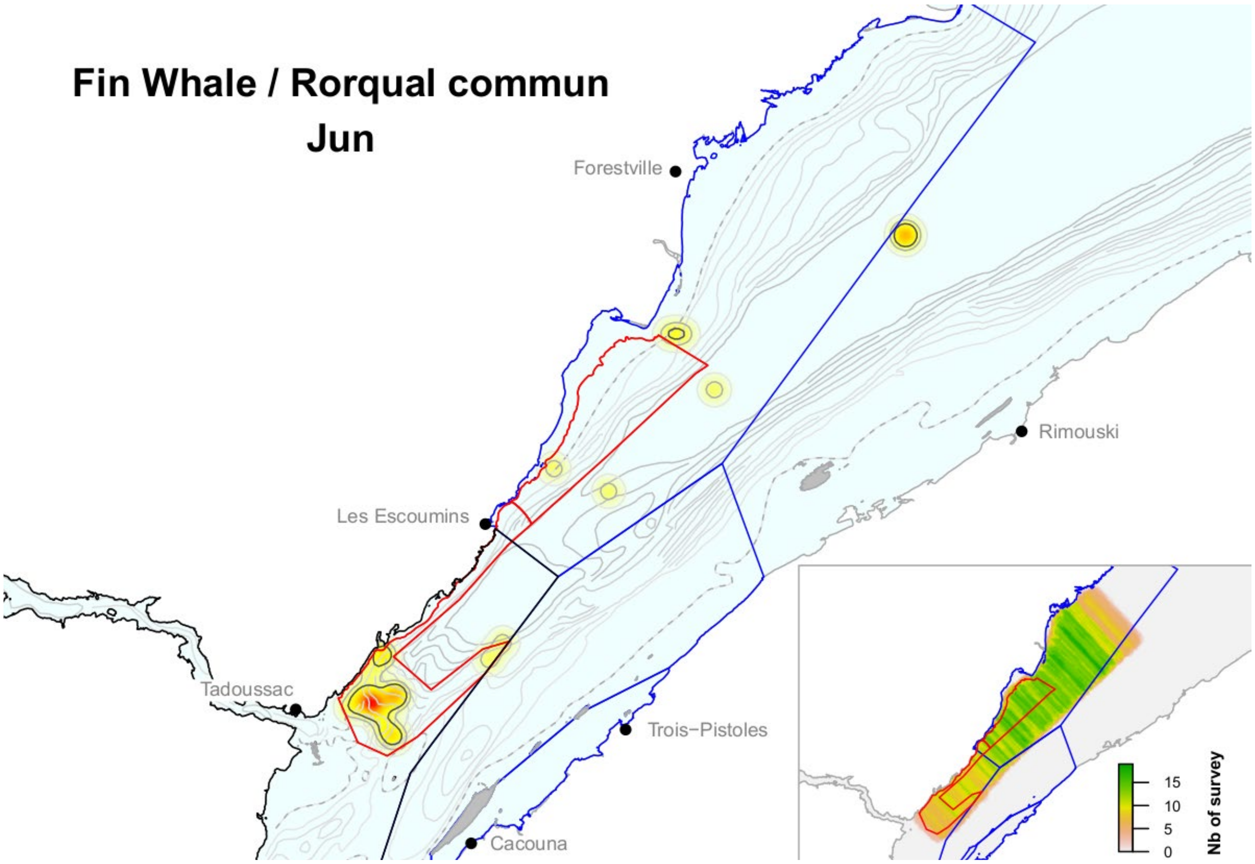


Appendix 6. Kernel representation of the monthly distribution of fin whale observations and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



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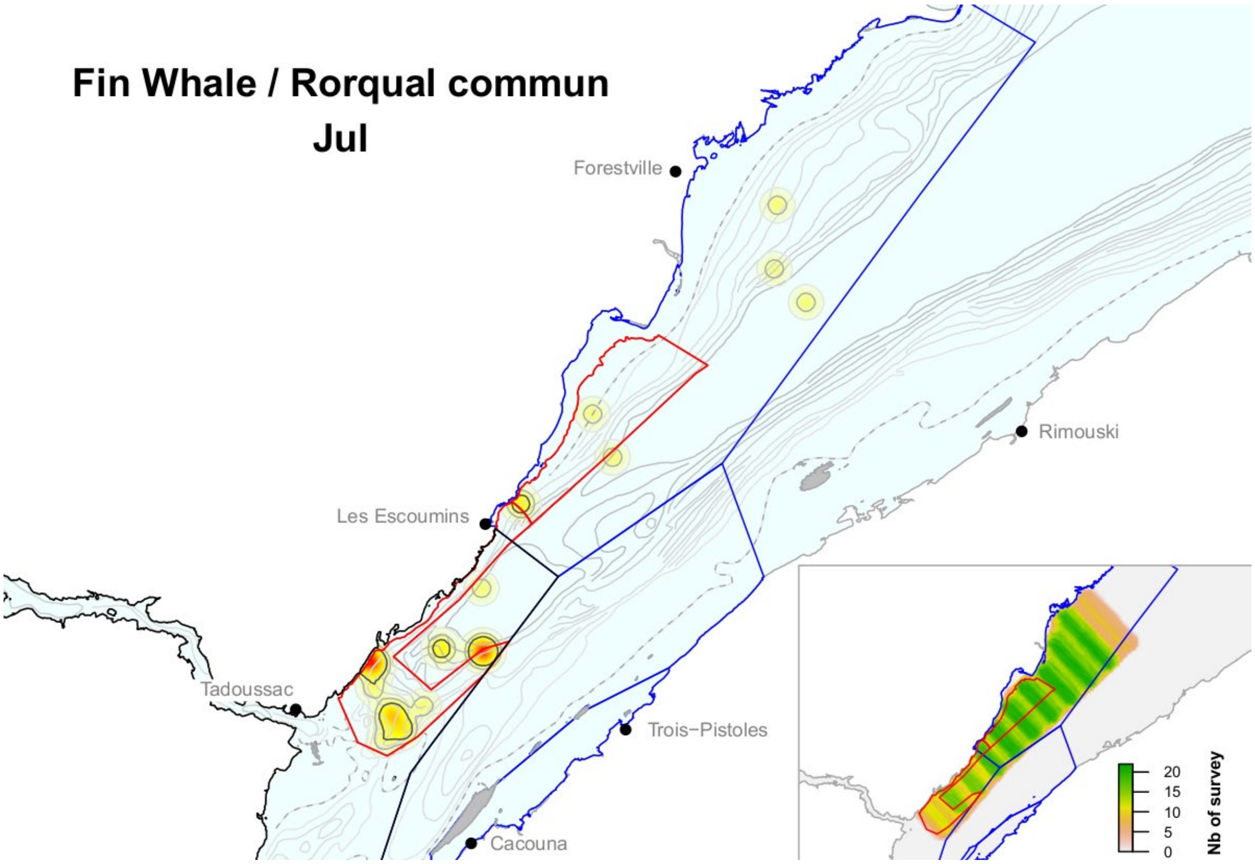

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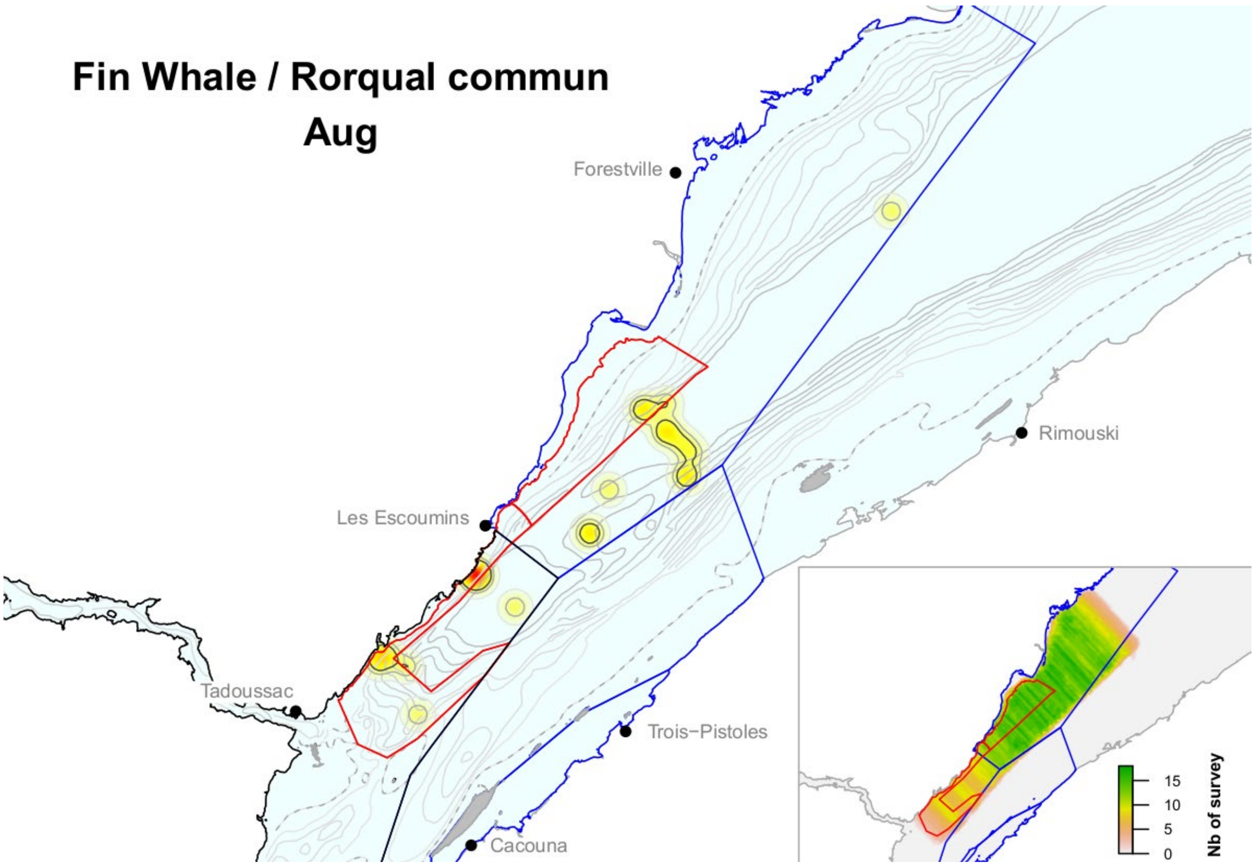

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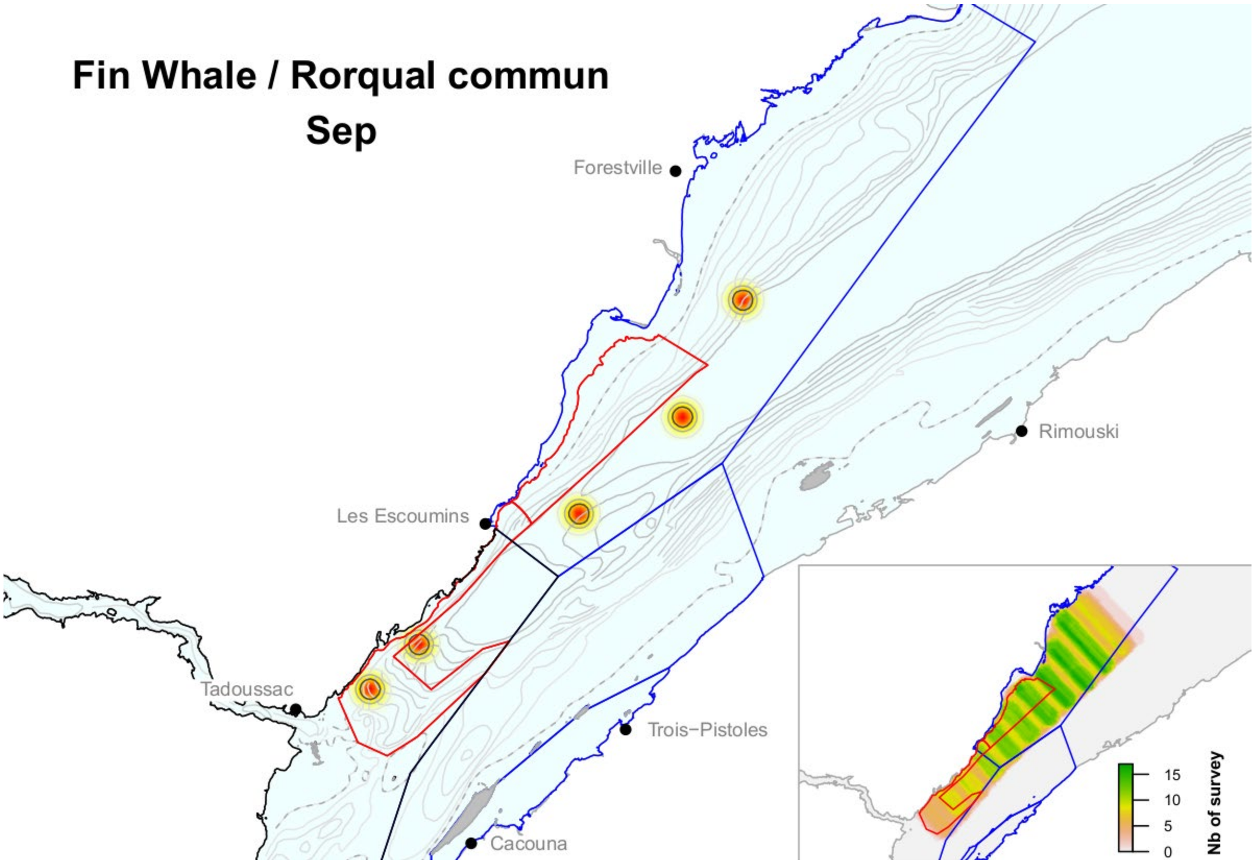

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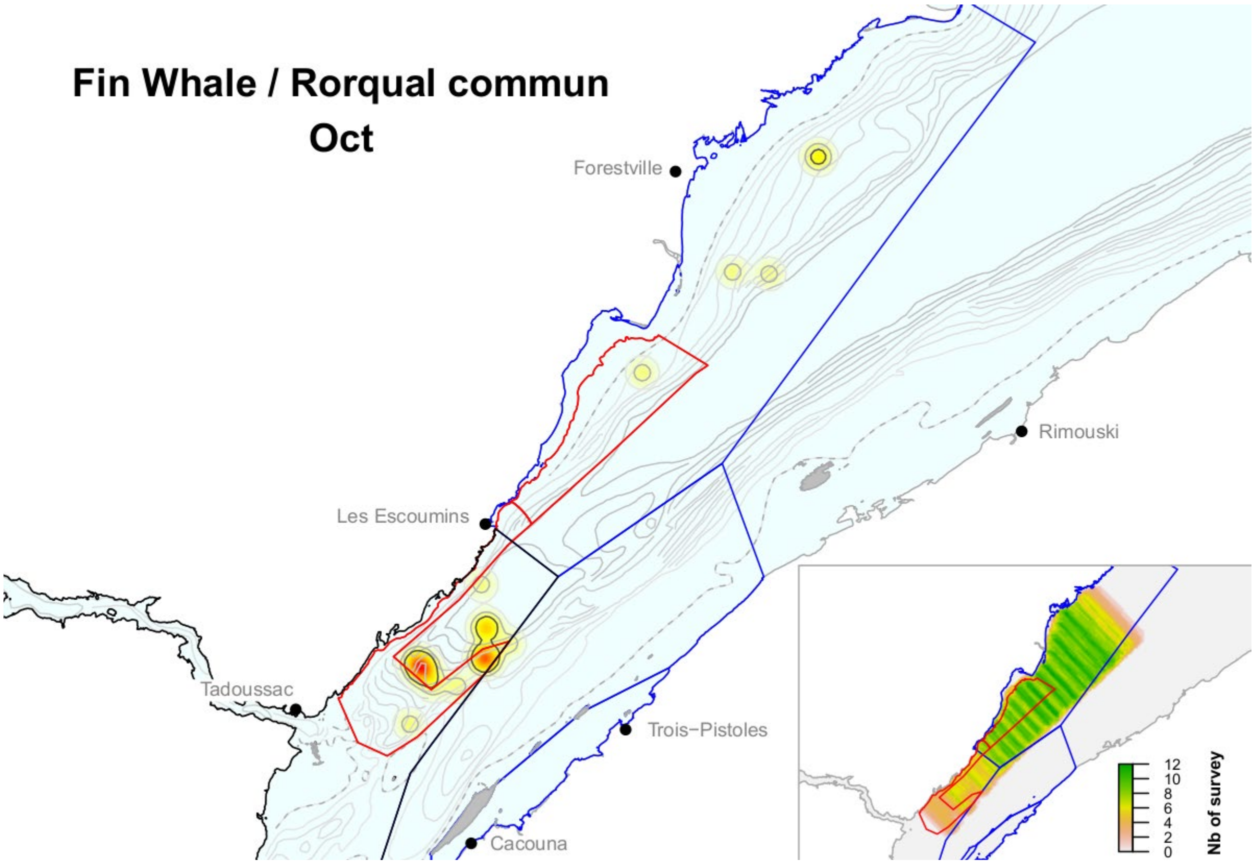

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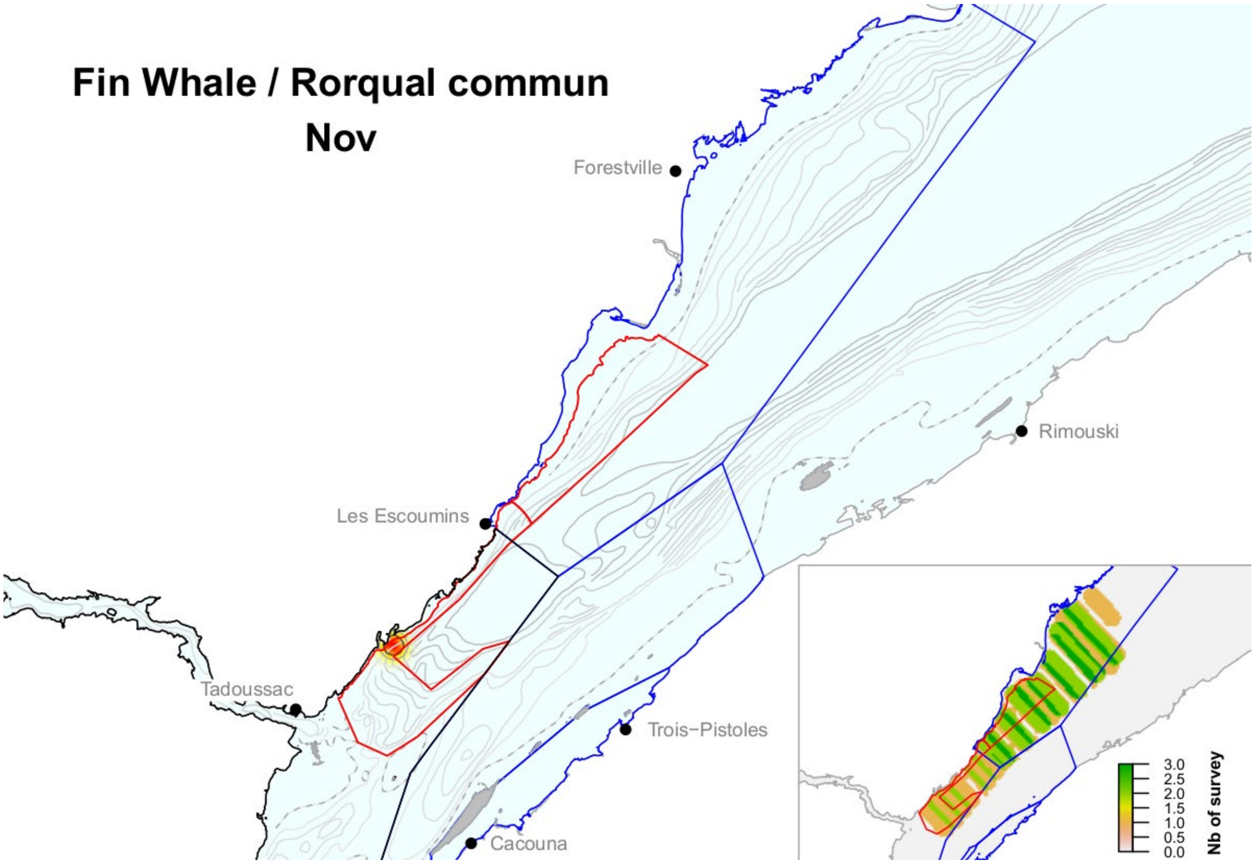

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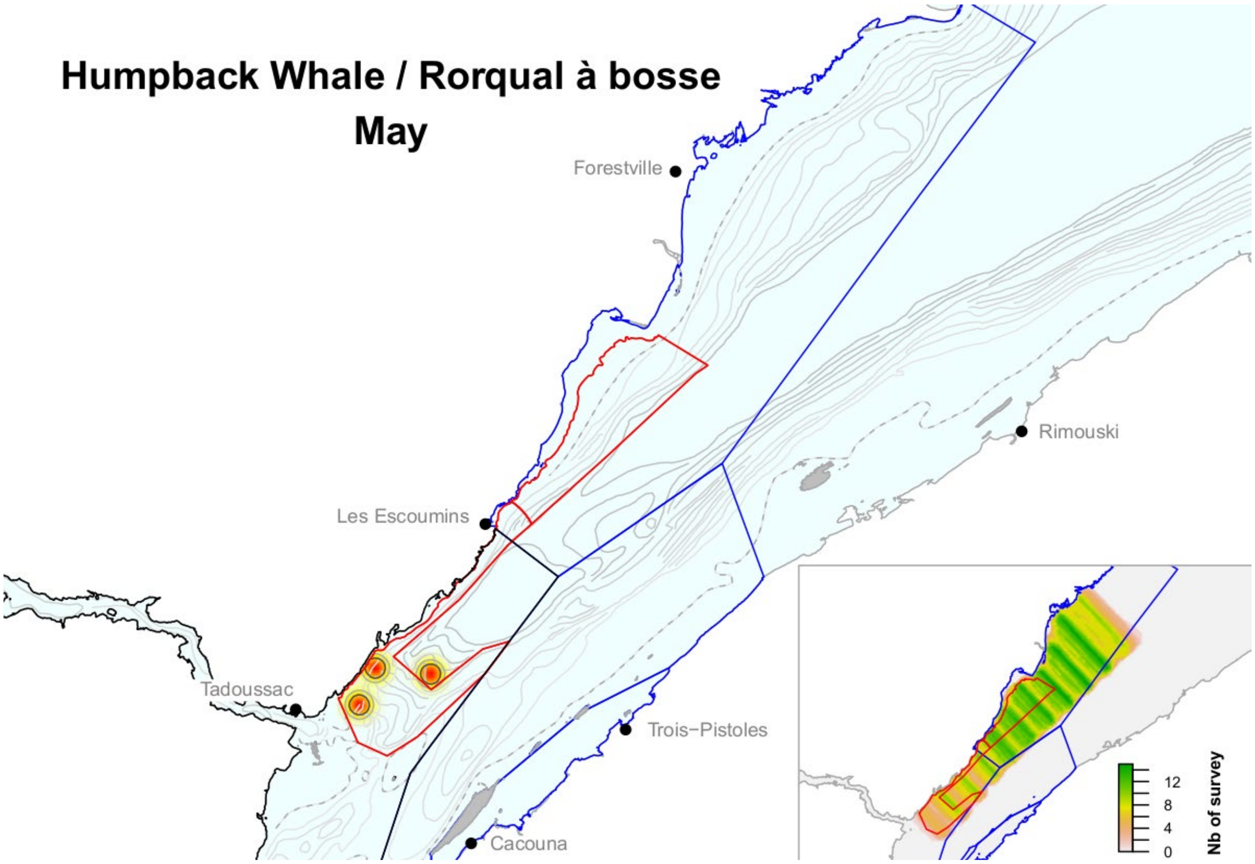
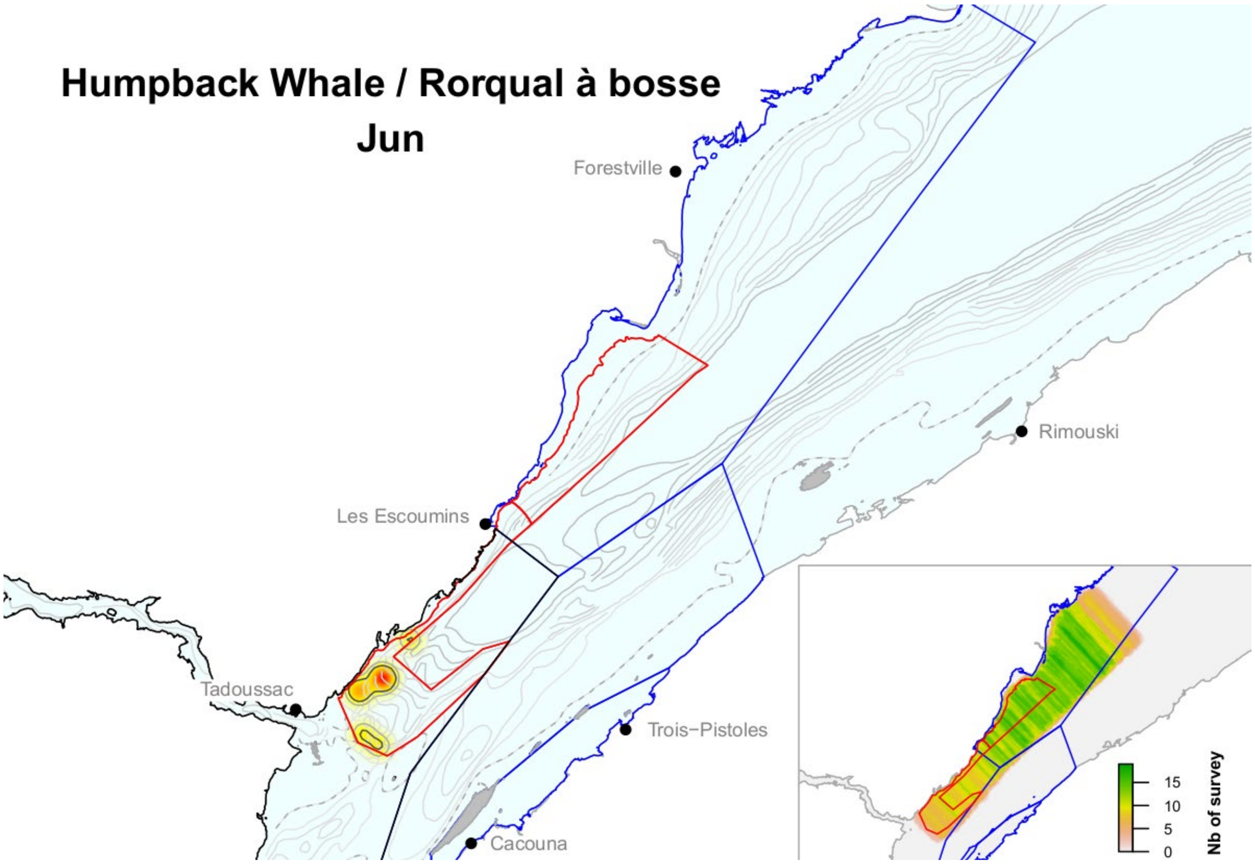


Appendix 7. Kernel representation of the monthly distribution of humpback whale observations and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



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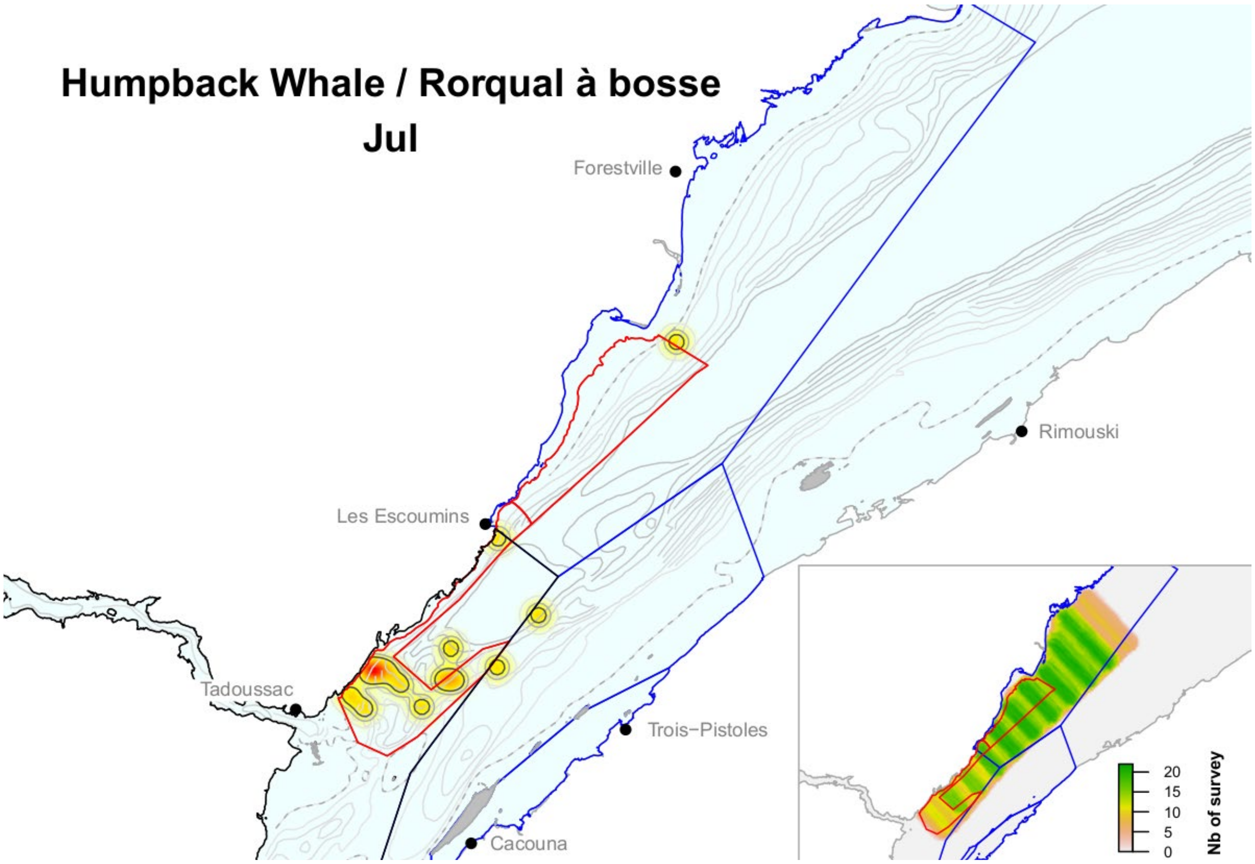

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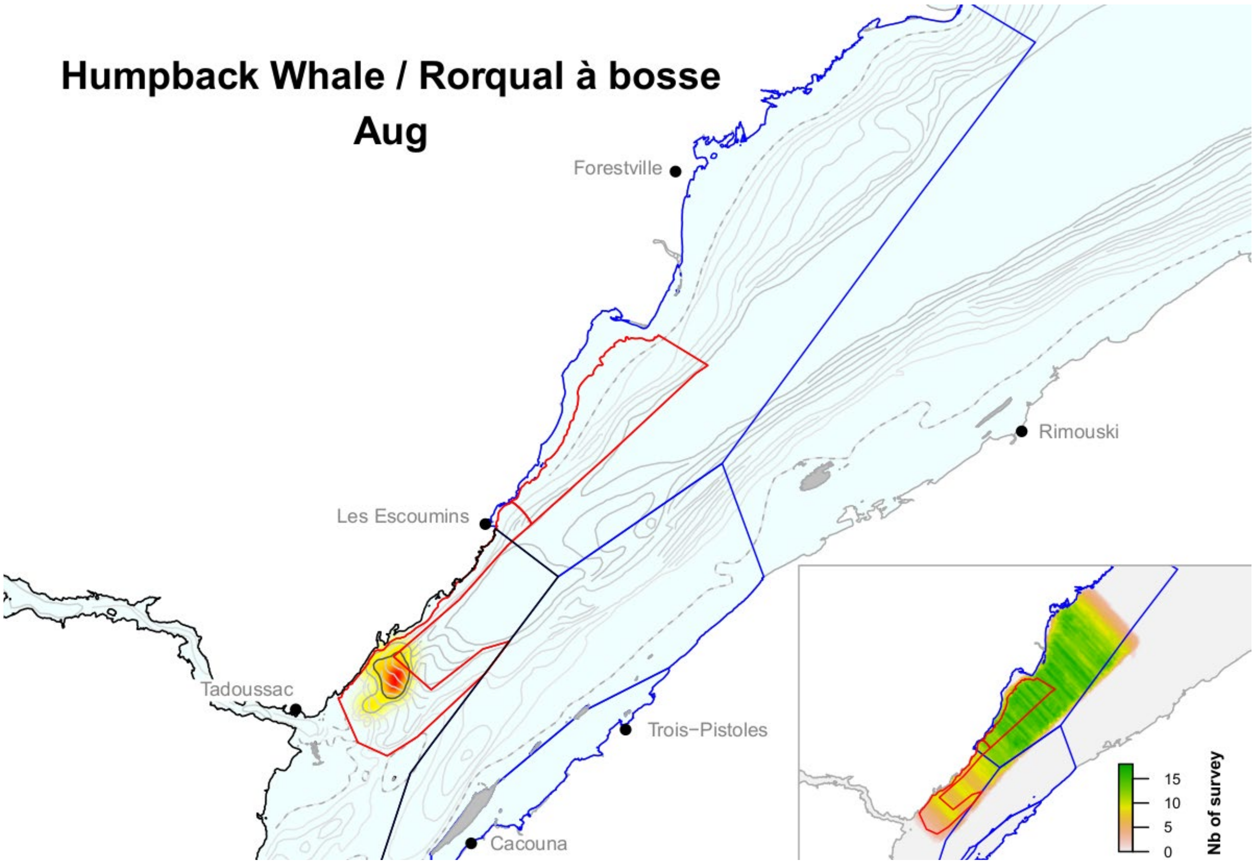

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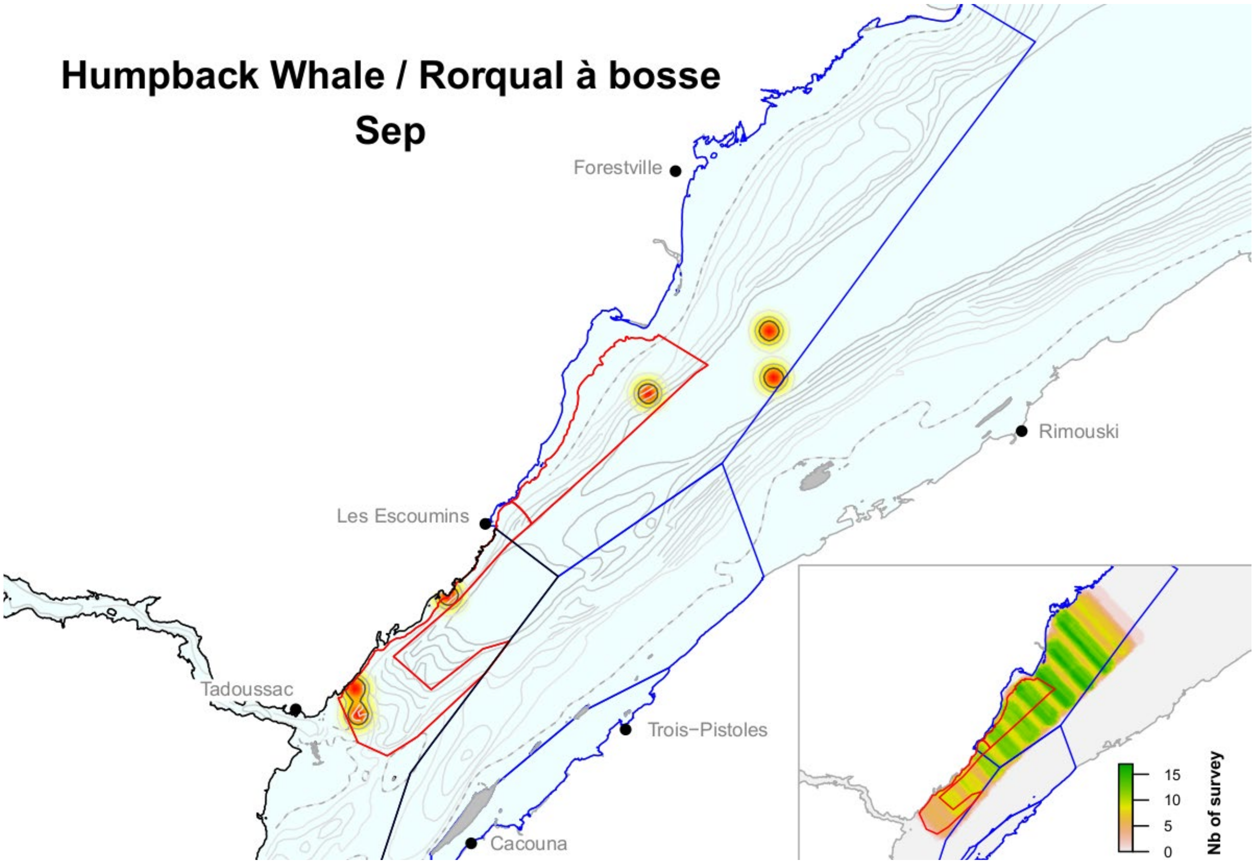

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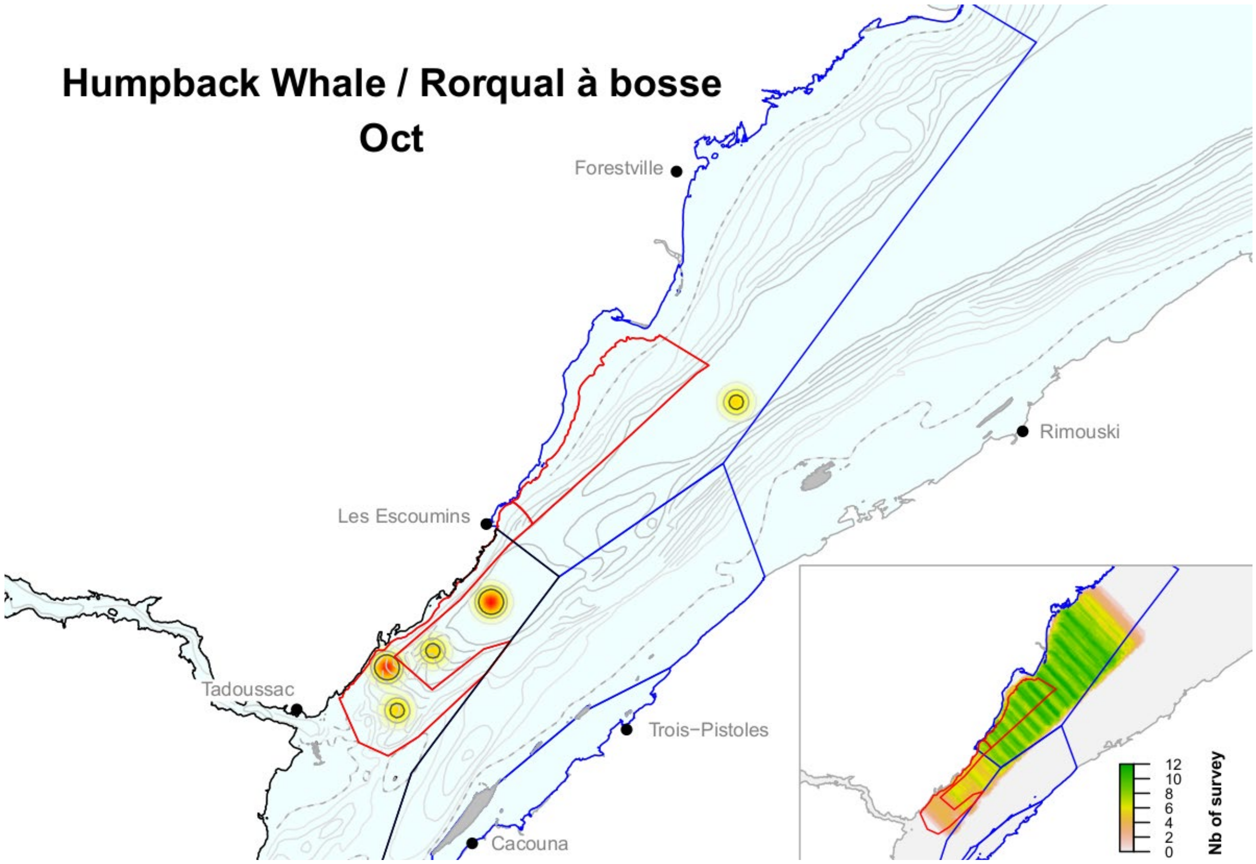

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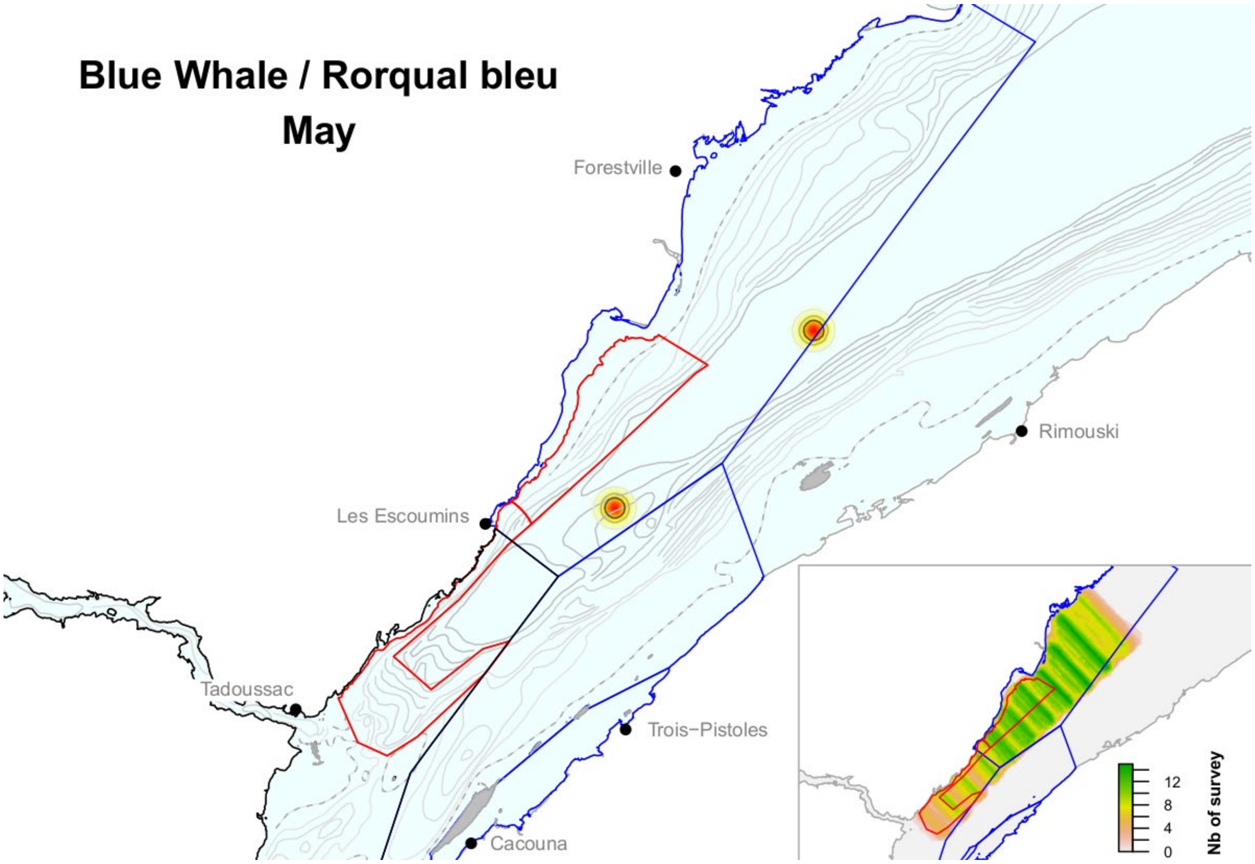
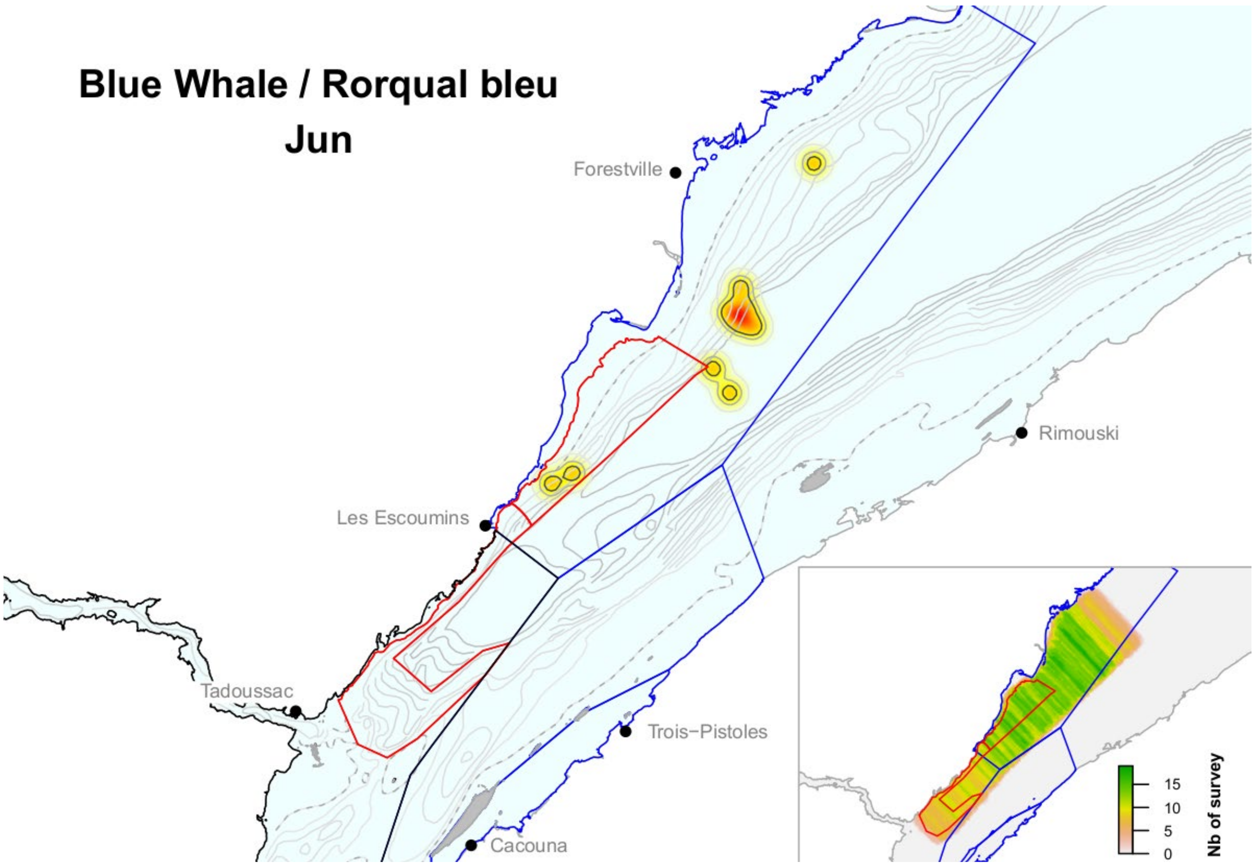


Appendix 8. Kernel representation of the monthly distribution of blue whale observations and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



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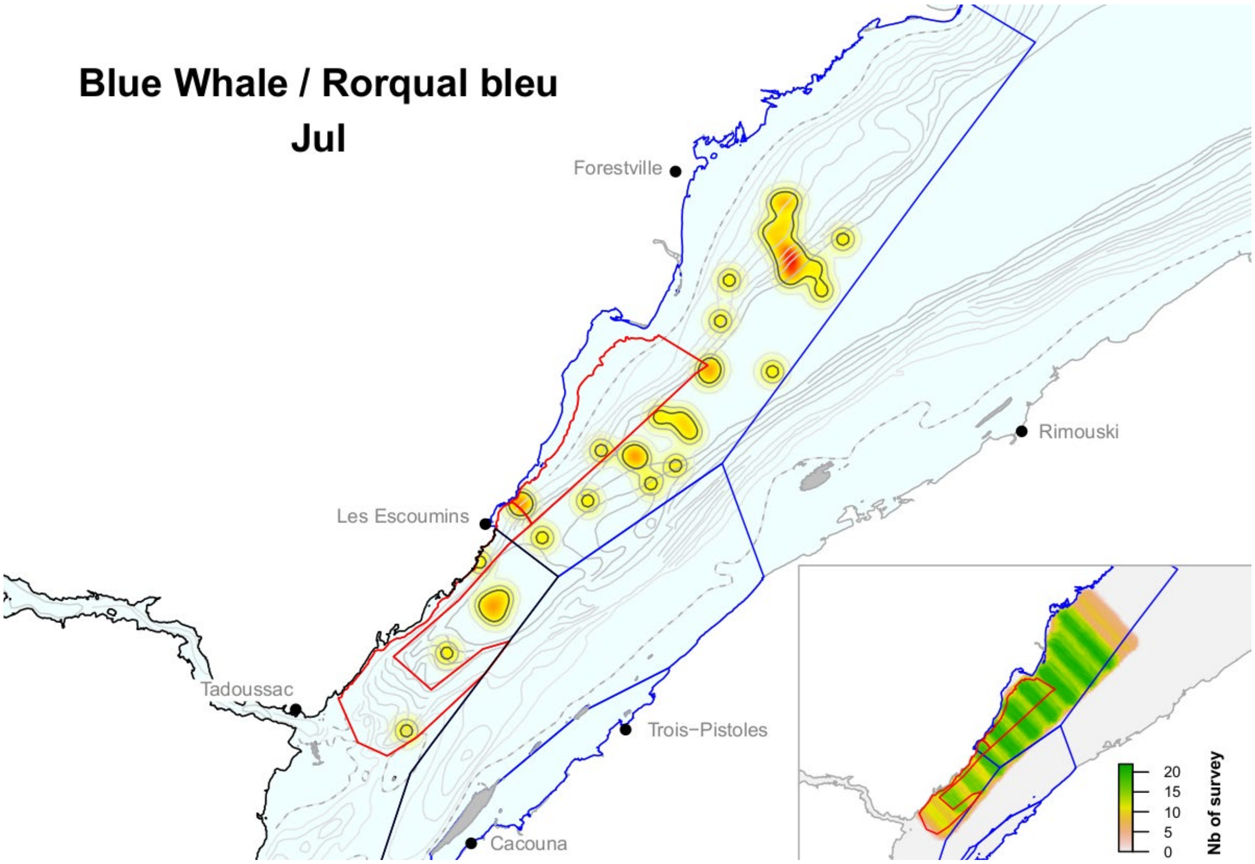

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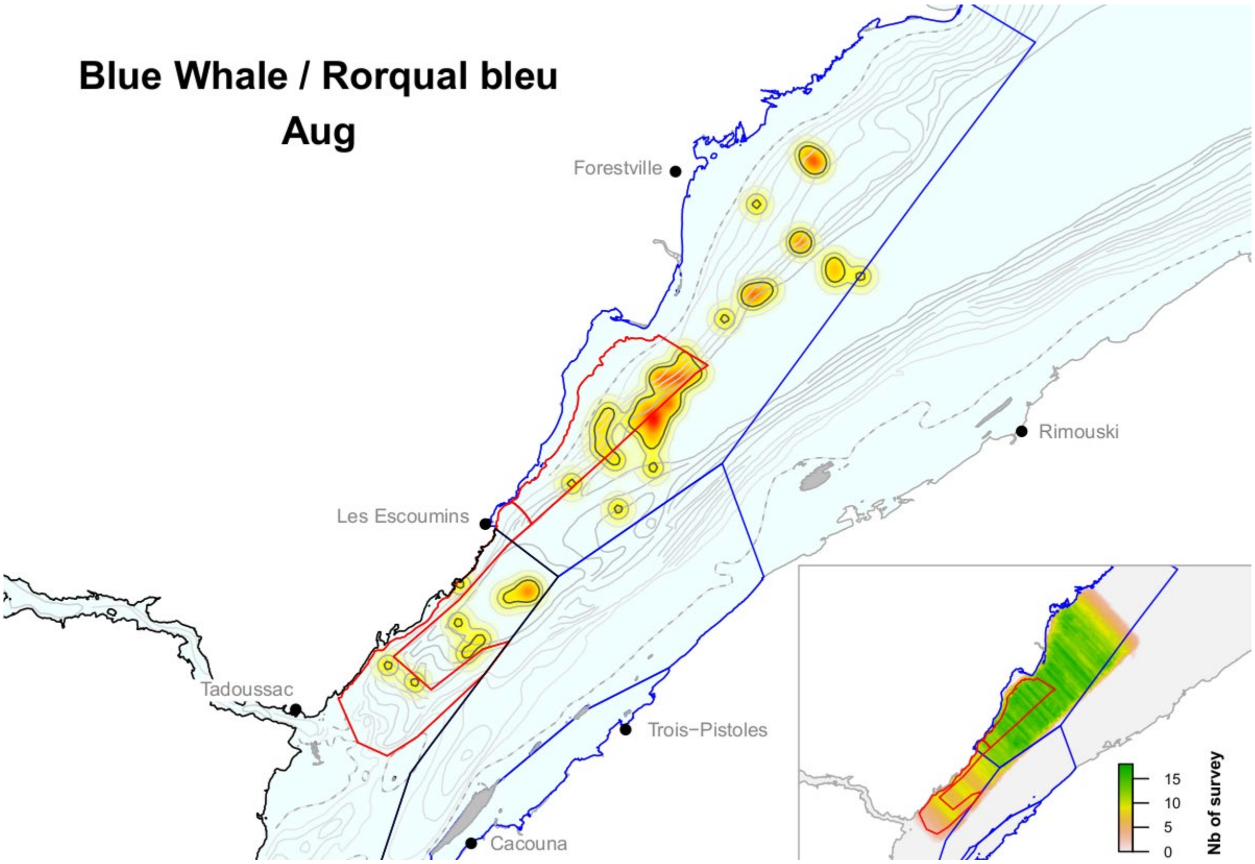

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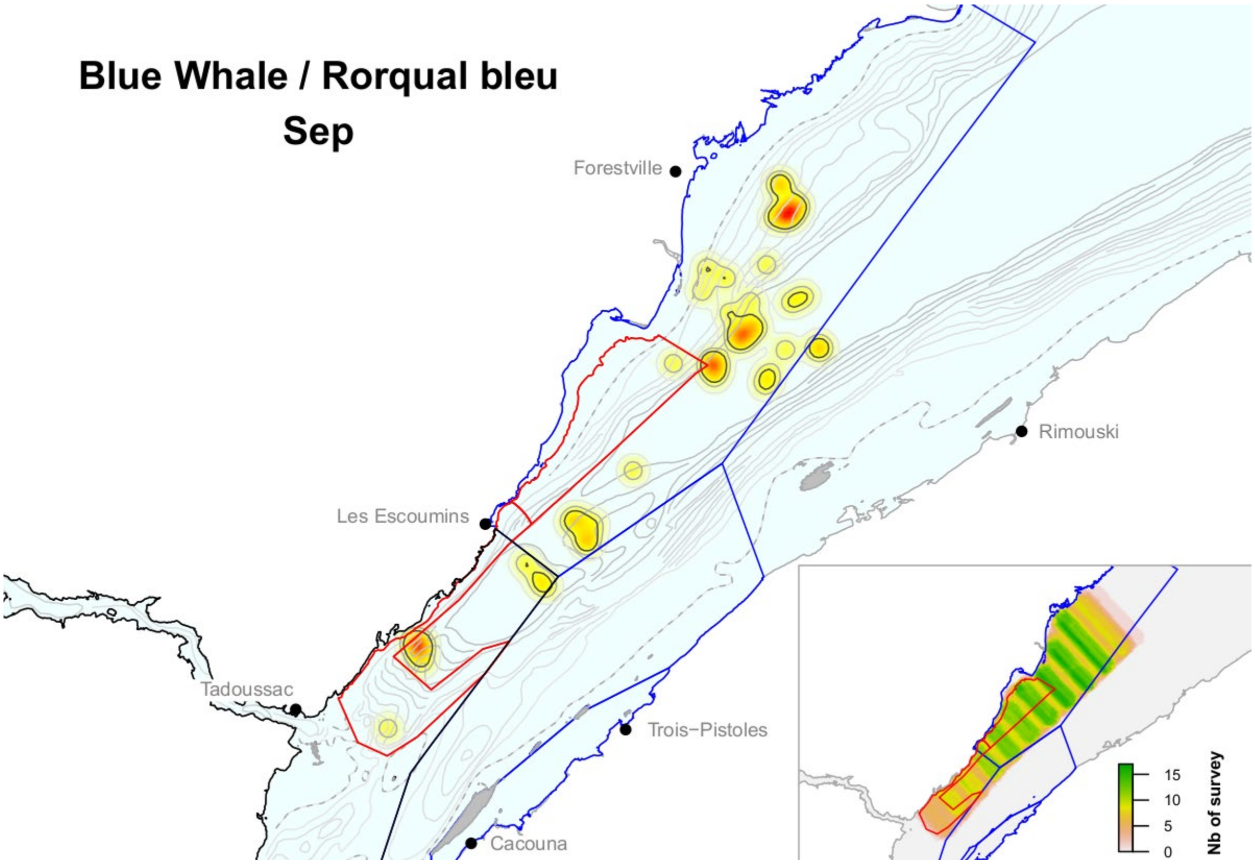

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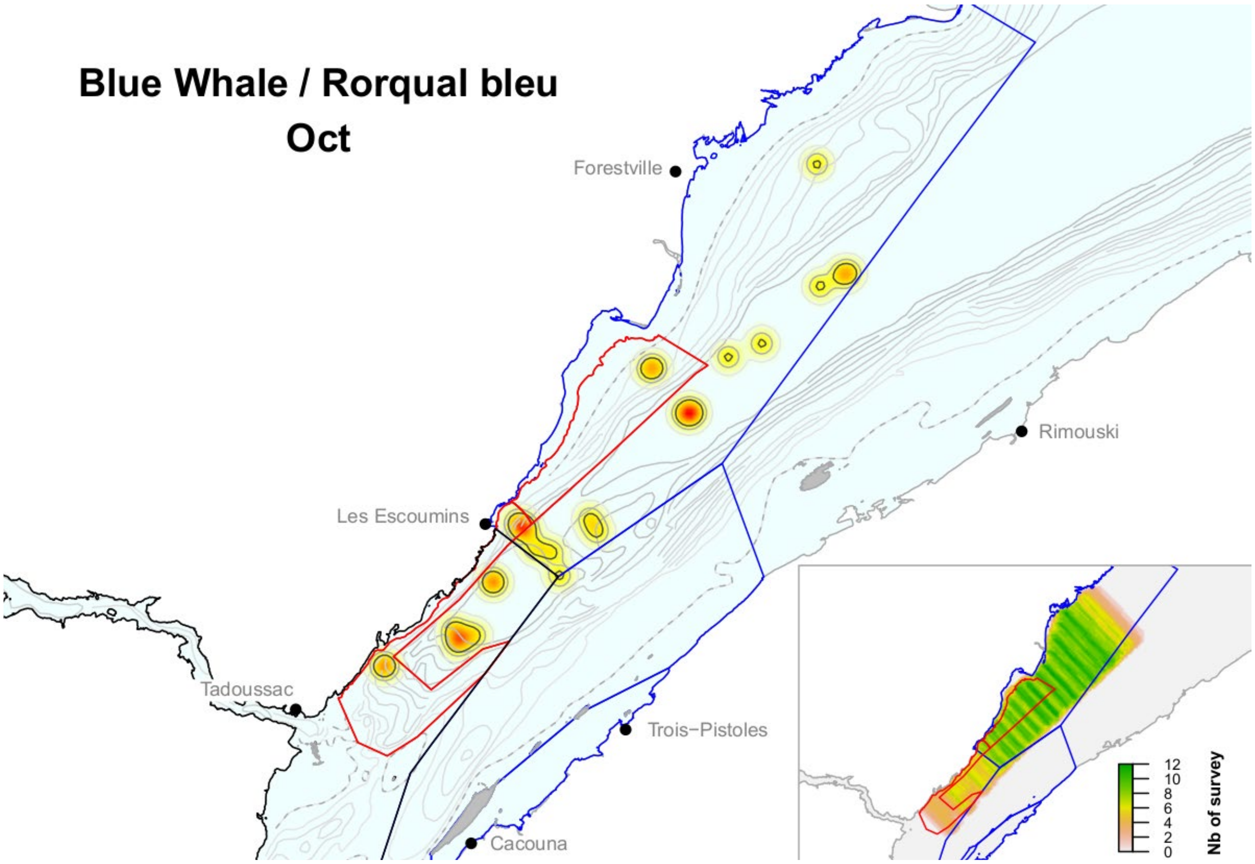

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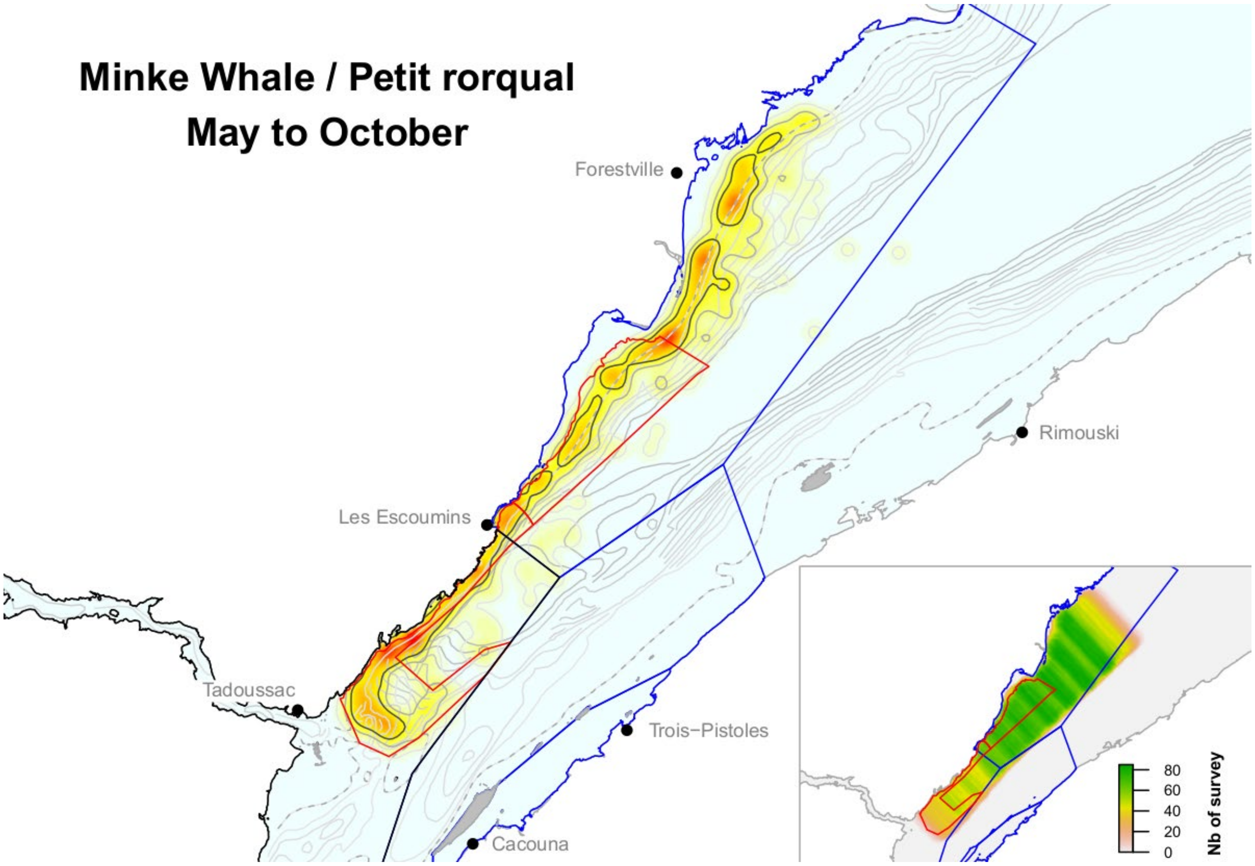
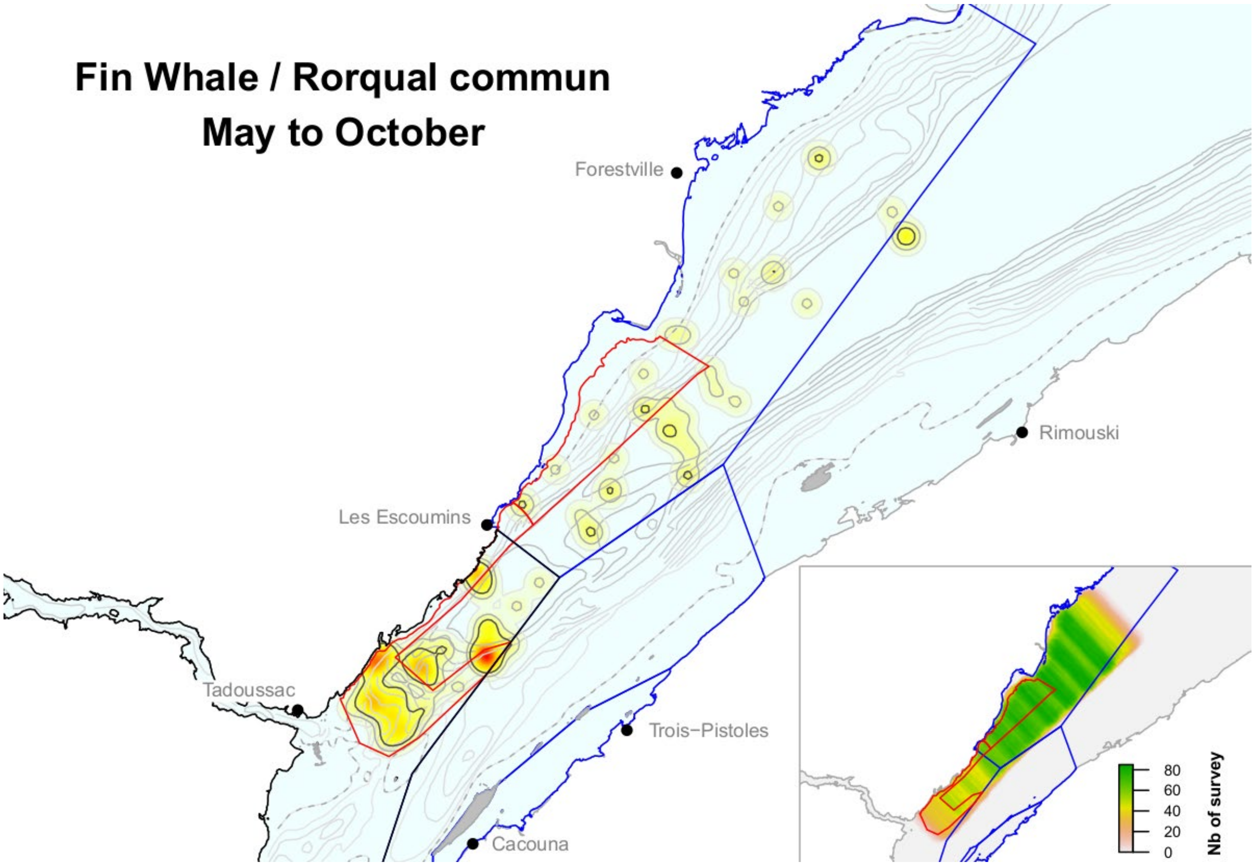
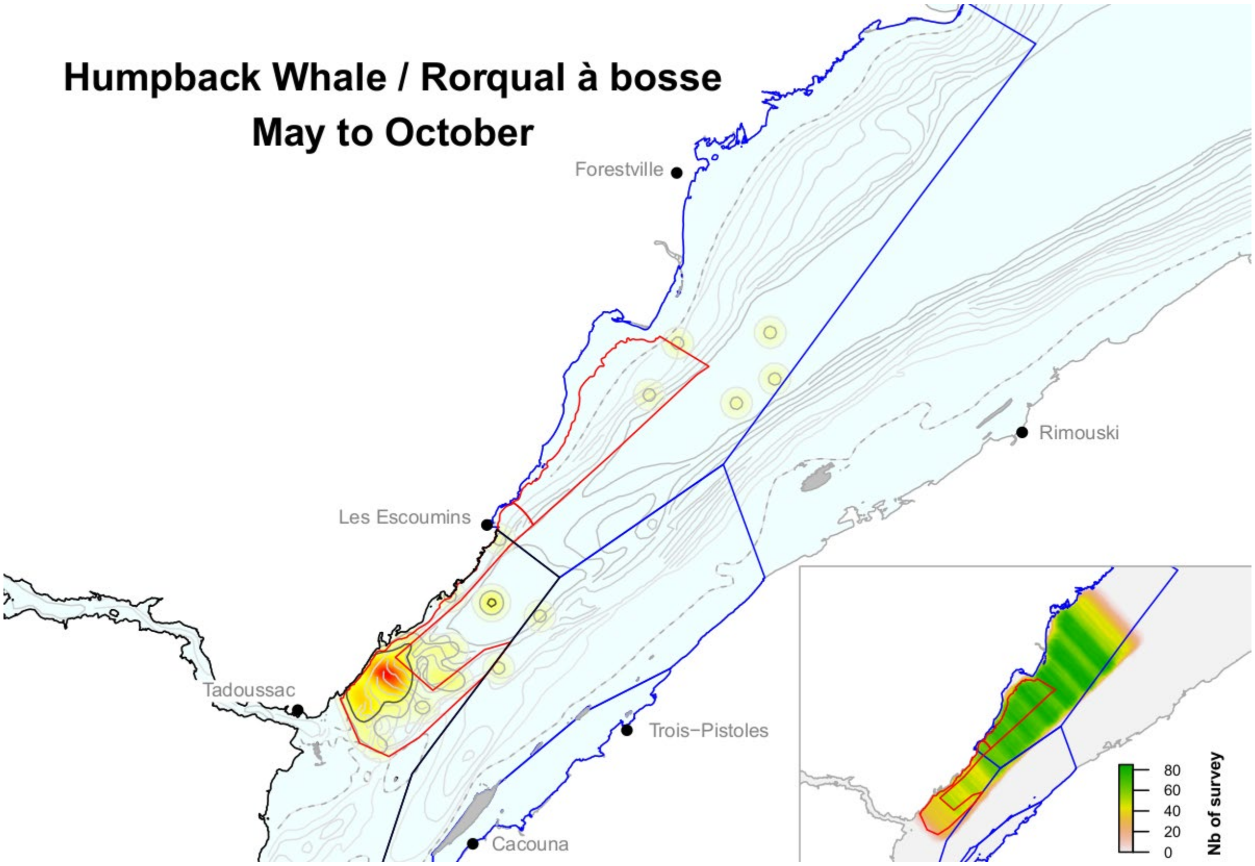


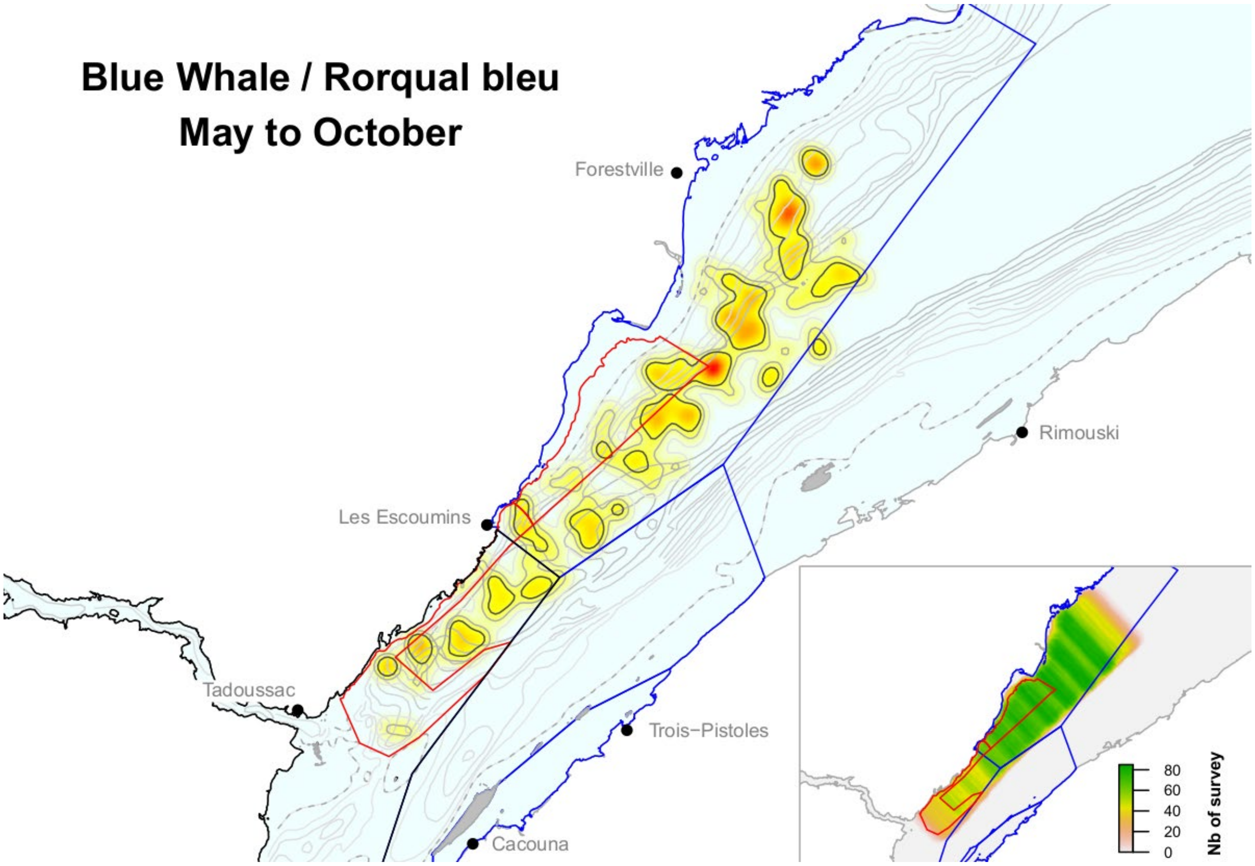
Appendix 9. Kernel representation of the distribution of minke whale observations from May to October and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



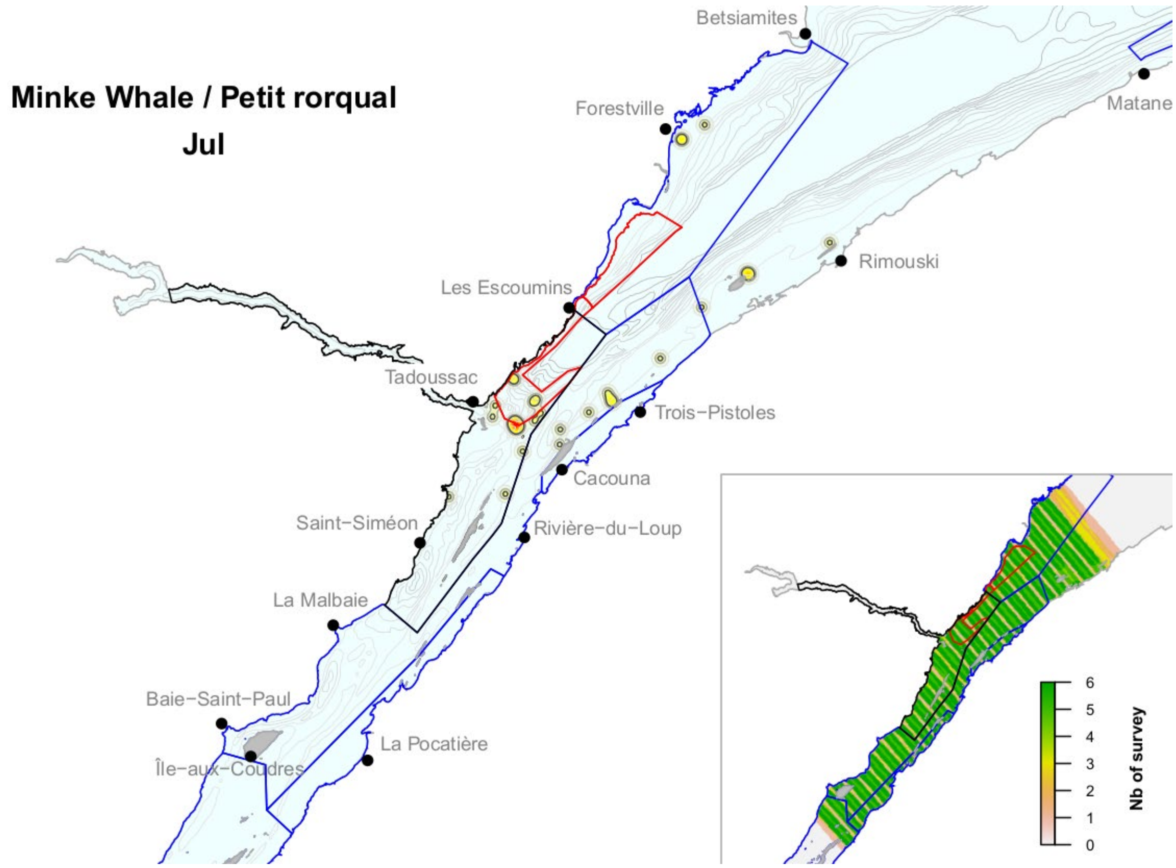
Appendix 10. Kernel representation of the distribution of fin whale observations from May to October and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



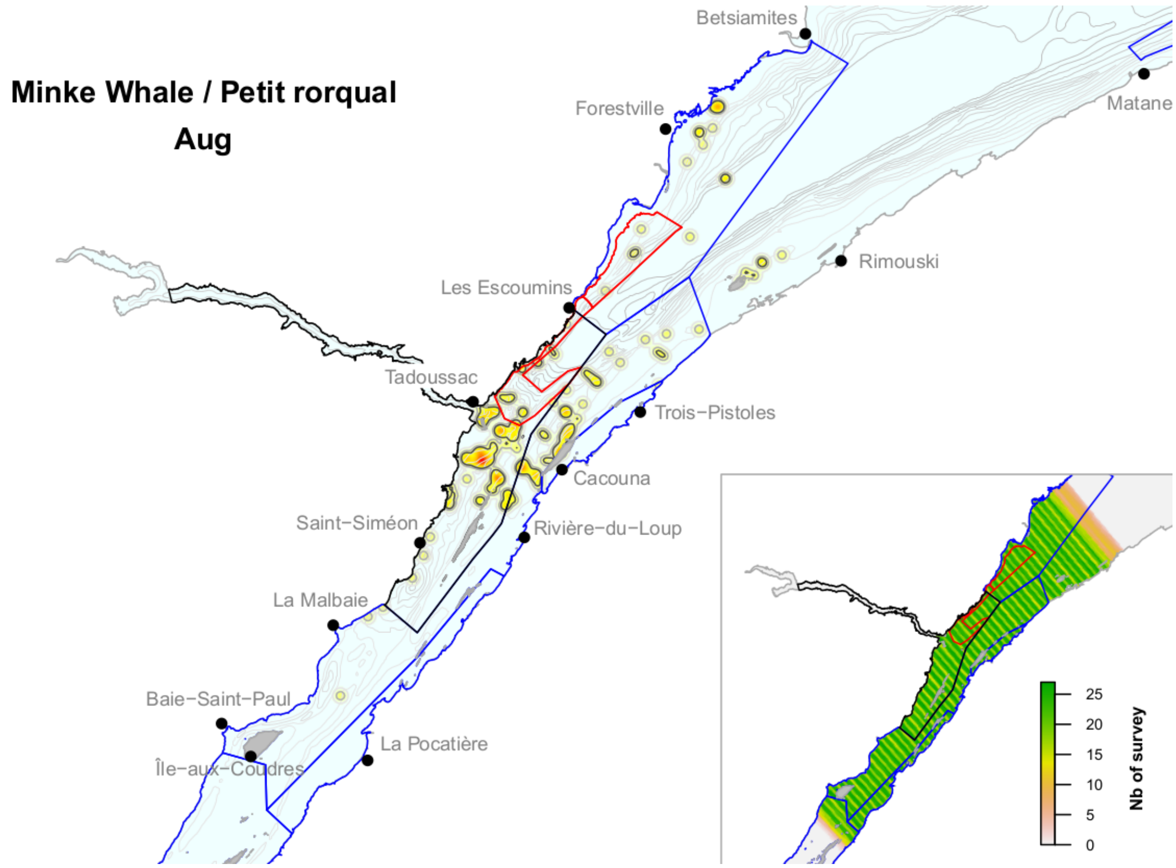
Appendix 11. Kernel representation of the distribution of humpback whale observations from May to October and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



Appendix 12. Kernel representation of the distribution of blue whale observations from May to October and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2009 and 2015. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines and the dotted isoline correspond to the 20 m isobaths.



Appendix 13. Kernel representation of the distribution of minke whale observations and observation effort in the St. Lawrence estuary based on systematic aerial surveys conducted in July between 2001 and 2016. Note: This map cover the zone from Ile-Aux-Coudres to Forestville-Rimouski including the most intensive observation effort. See the complementary maps (Appendix 14) covering Forestville-Rimouski to the downstream portion of the Estuary. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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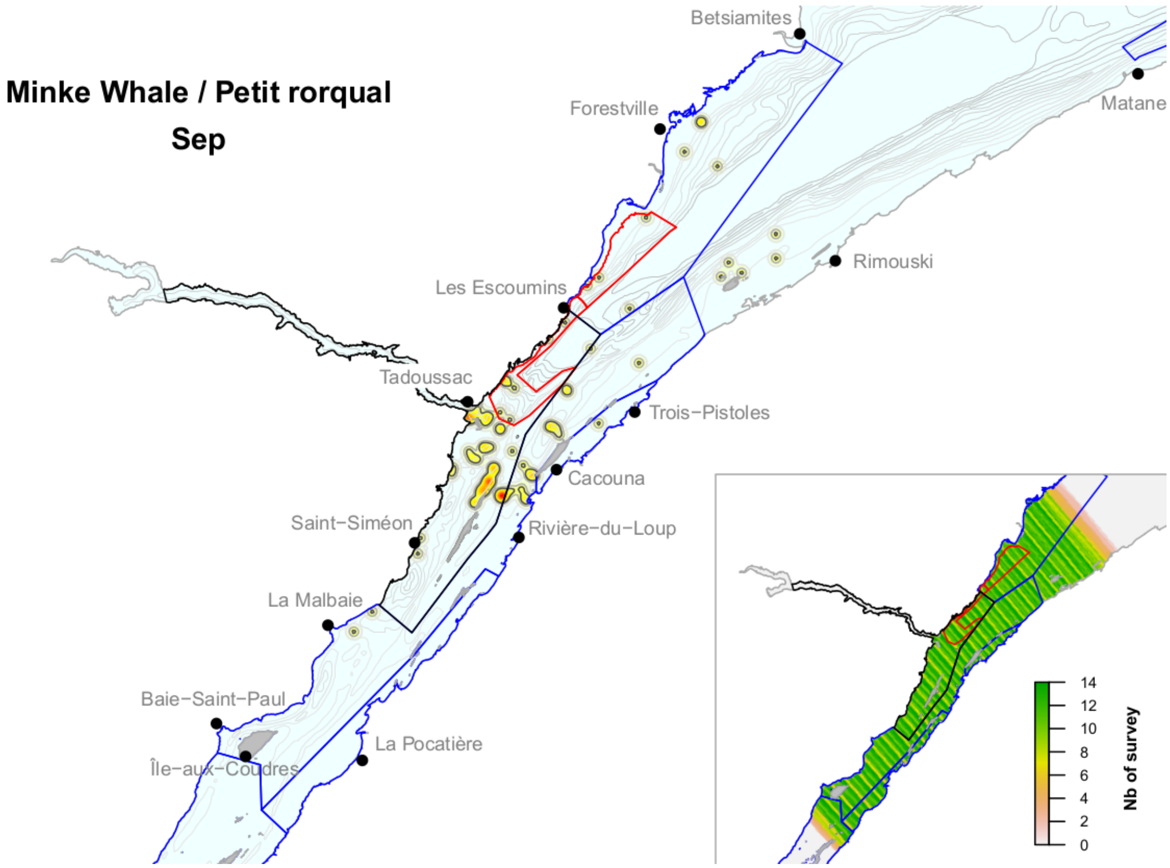

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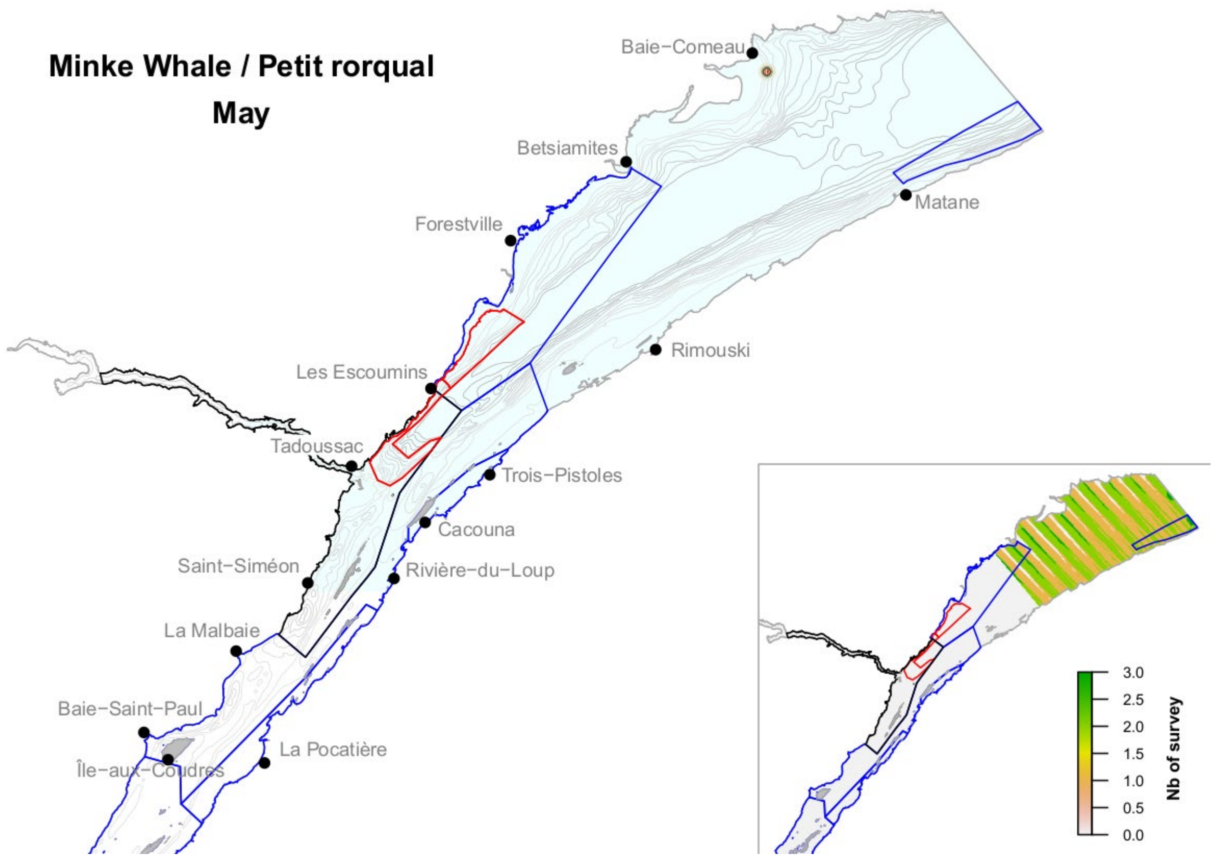
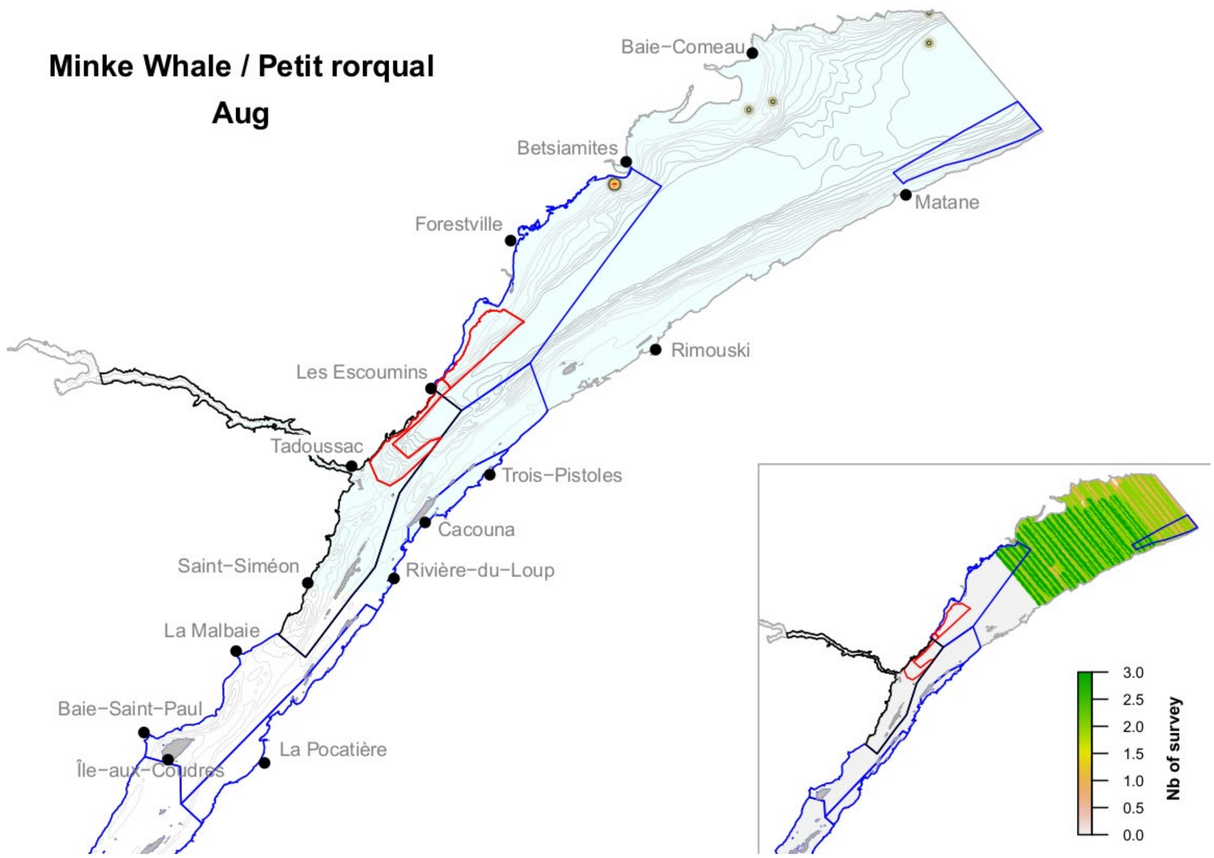


Appendix 14. Kernel representation of the distribution of minke whale observations and observation effort in the St. Lawrence estuary based on systematic aerial surveys conducted in May between 2001 and 2016. Note: This map cover the zone from Forestville-Rimouski to the downstream portion of the Estuary including the less intensive observation effort. See the complementary maps (Appendix 13) covering Ile-Aux-Coudres to Forestville-Rimouski. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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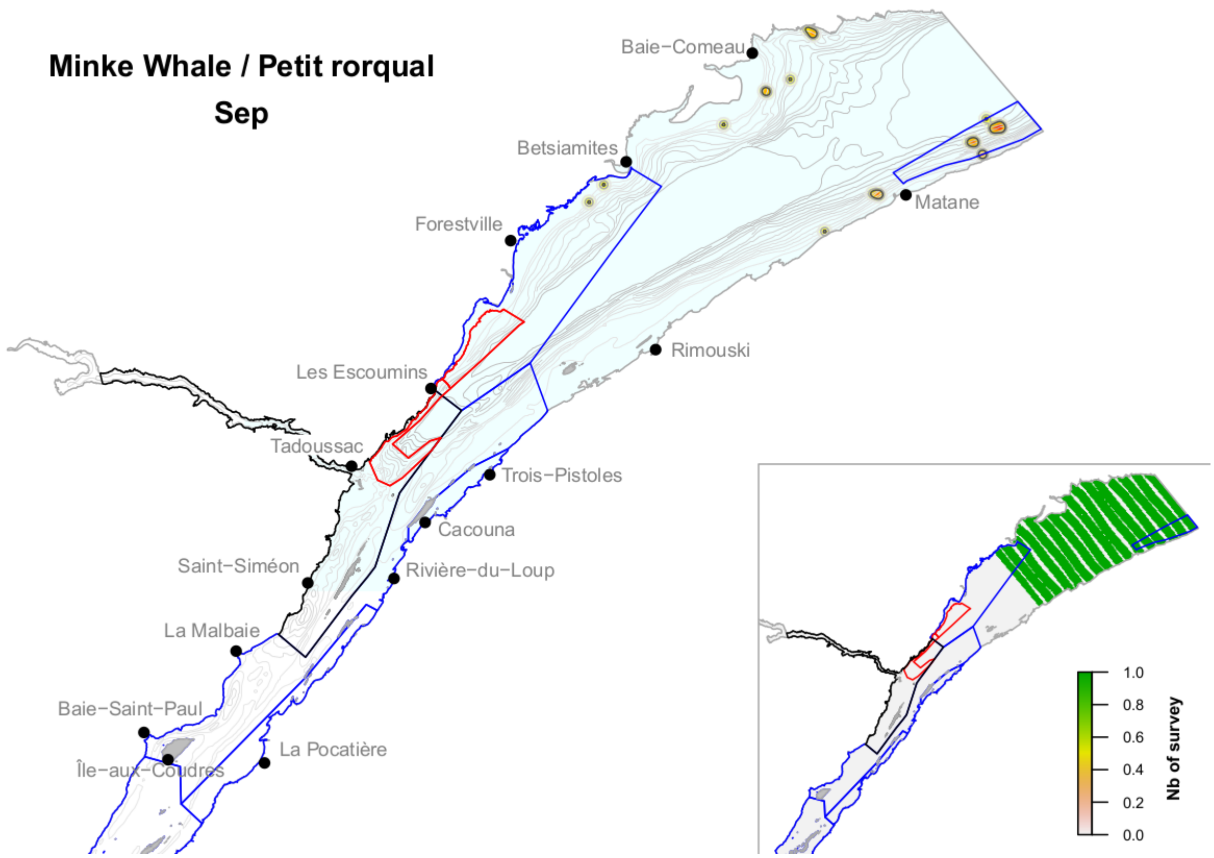

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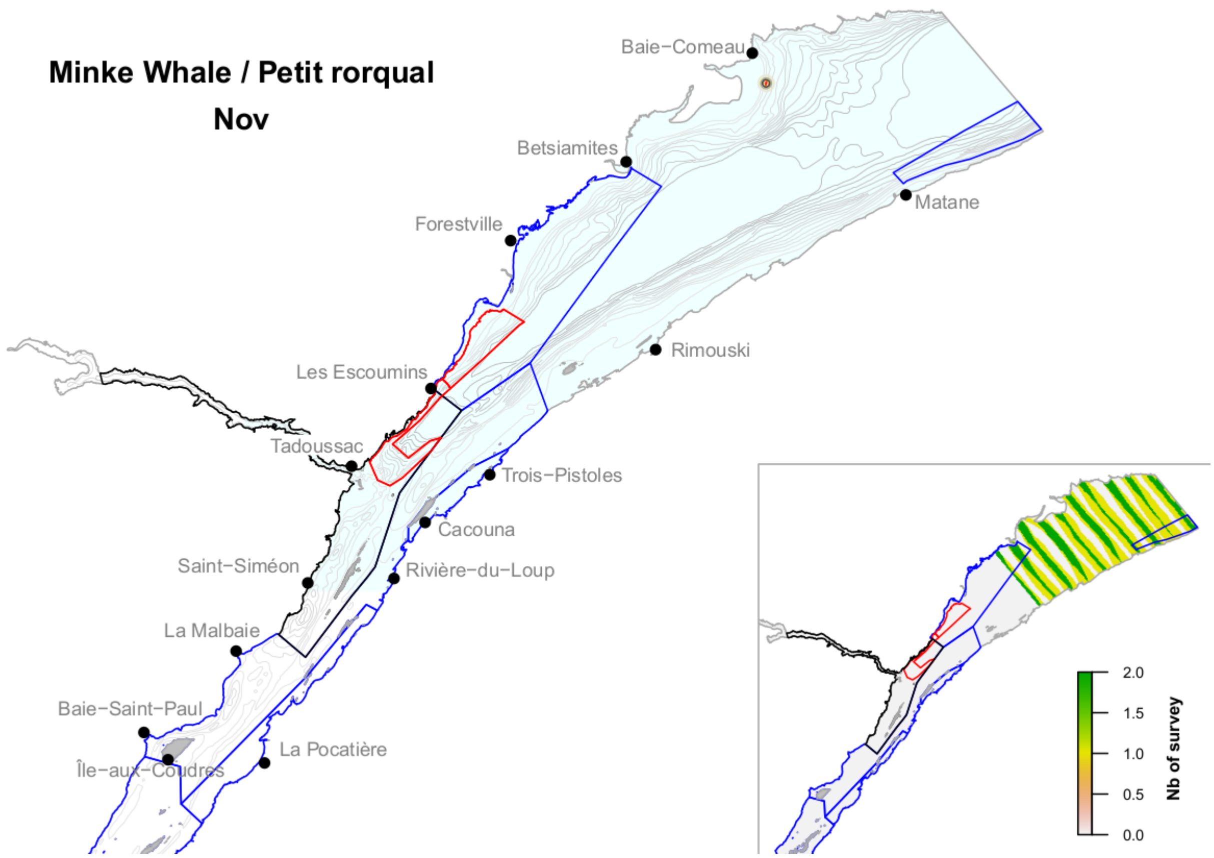

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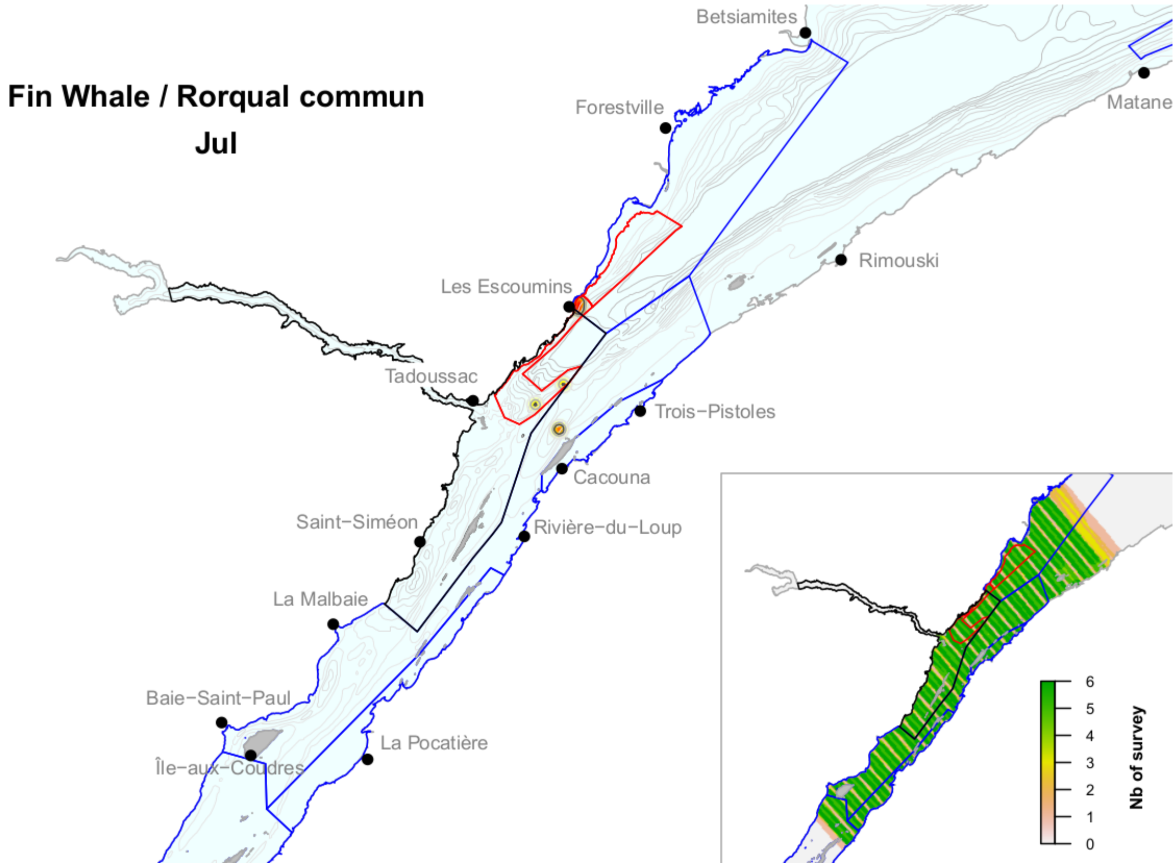
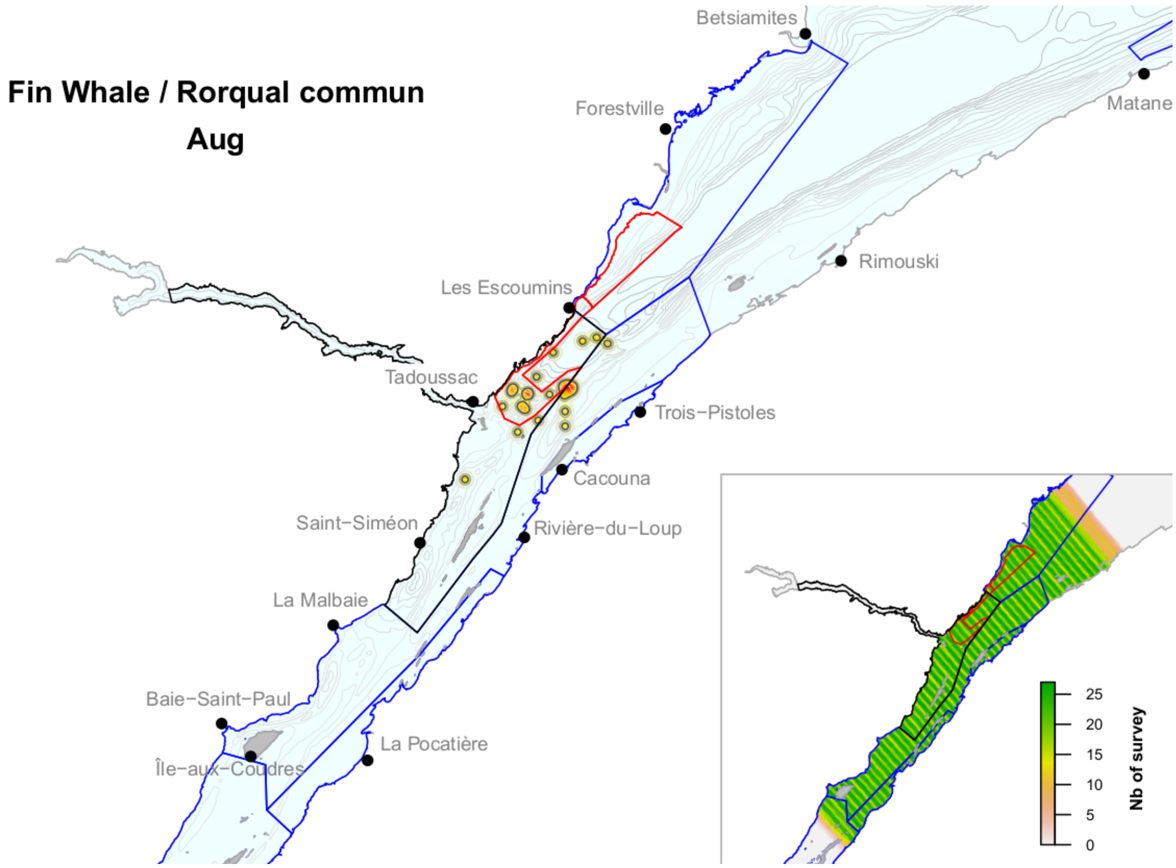


Appendix 15. Kernel representation of the distribution of fin whale observations and observation effort in the St. Lawrence estuary based on systematic aerial surveys conducted in July between 2001 and 2016. Note: This map covers the zone from Ile-Aux-Coudres to Forestville-Rimouski including the most intensive observation effort. No observations were recorded in the section covering Forestville-Rimouski to the downstream portion of the Estuary. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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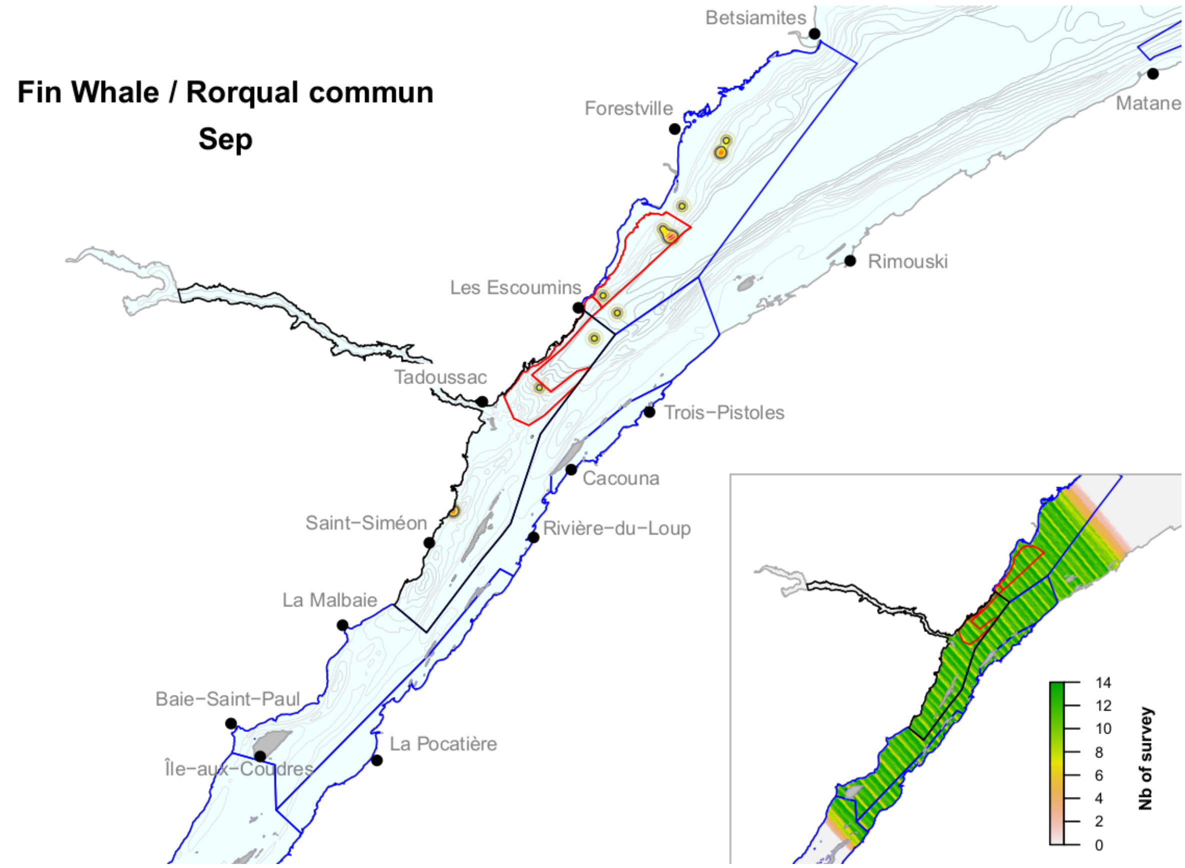

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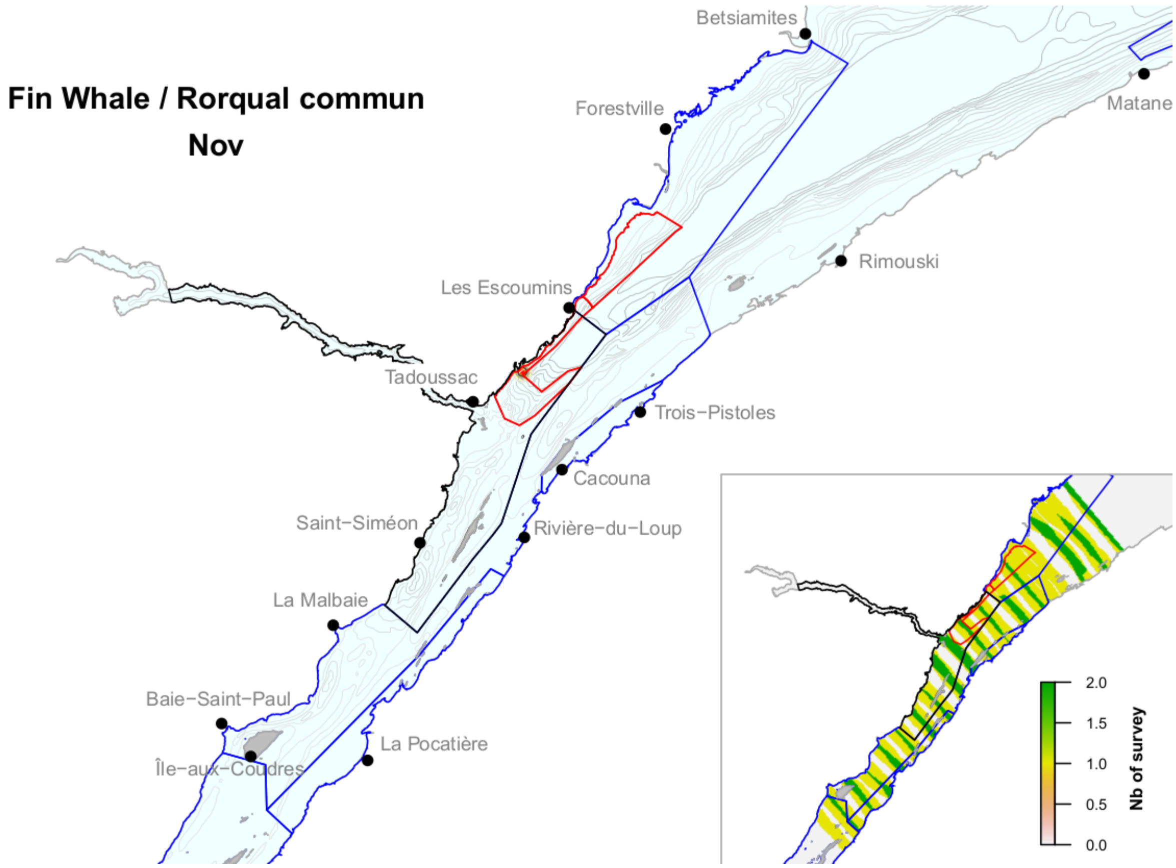

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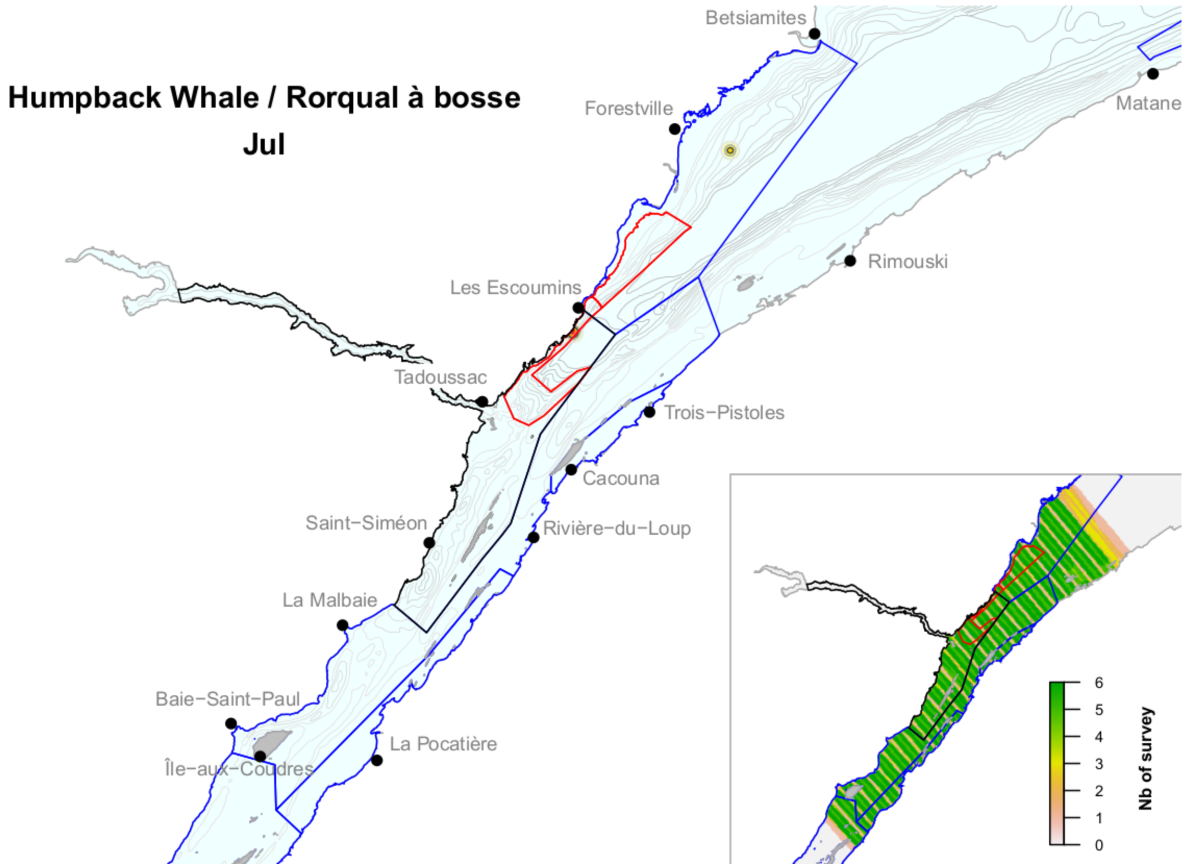
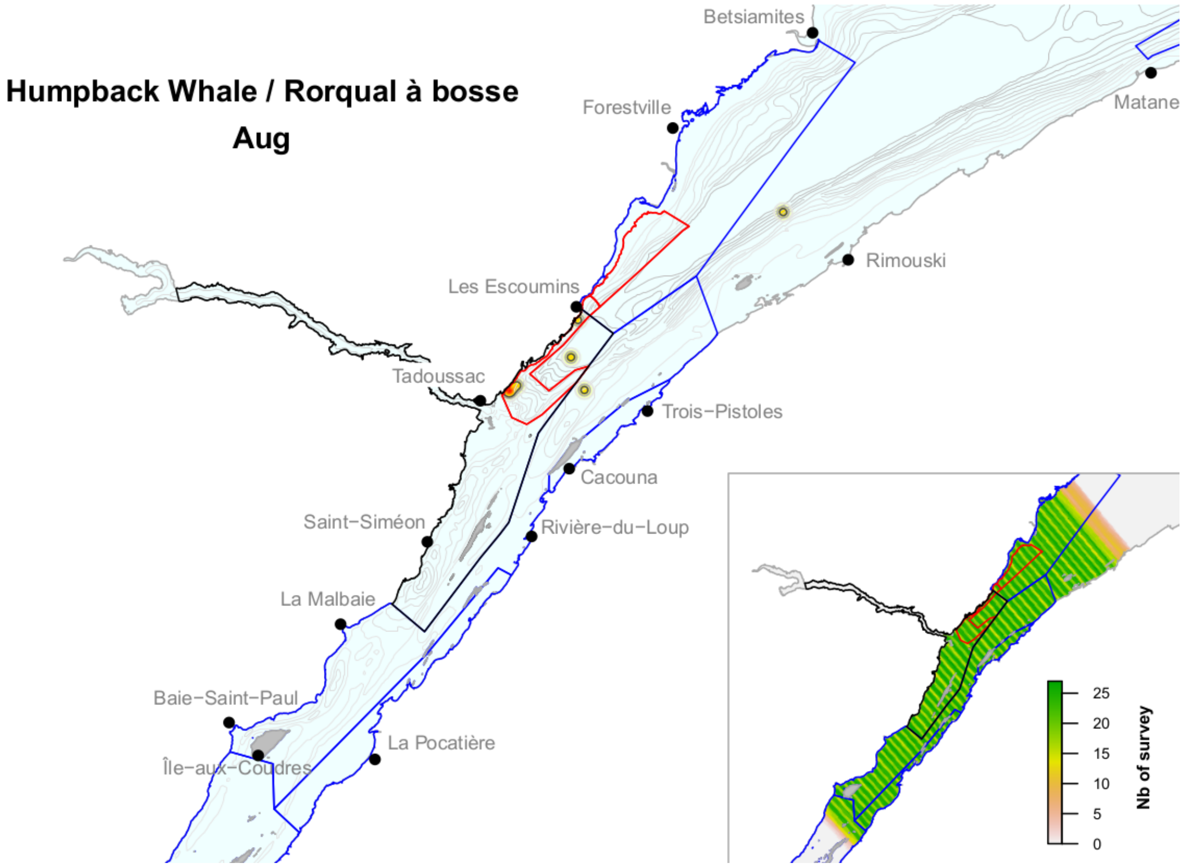


Appendix 16. Kernel representation of the distribution of humpback whale observations and observation effort in the St. Lawrence estuary based on systematic aerial surveys conducted in July between 2001 and 2016. Note: This map covers the zone from Ile-Aux-Coudres to Forestville-Rimouski including the most intensive observation effort. No observations were recorded in the section covering Forestville-Rimouski to the downstream portion of the Estuary. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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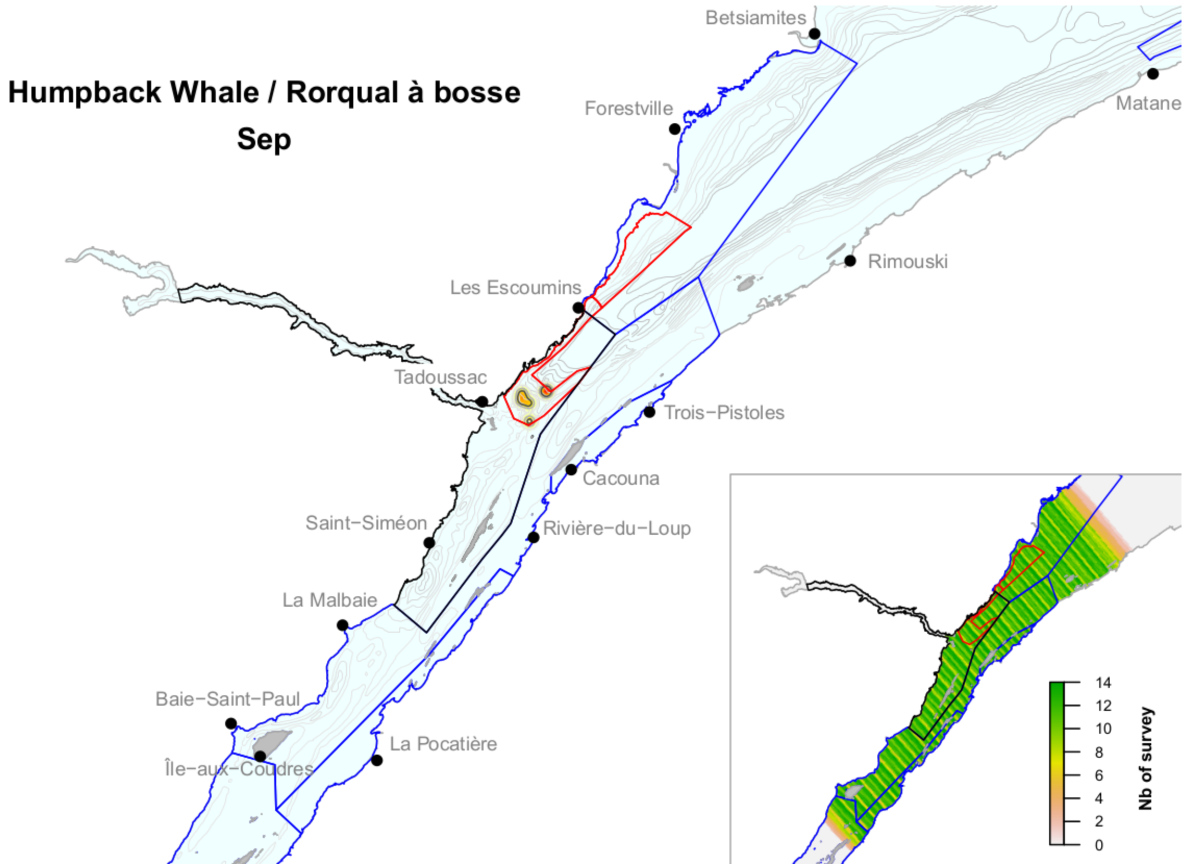

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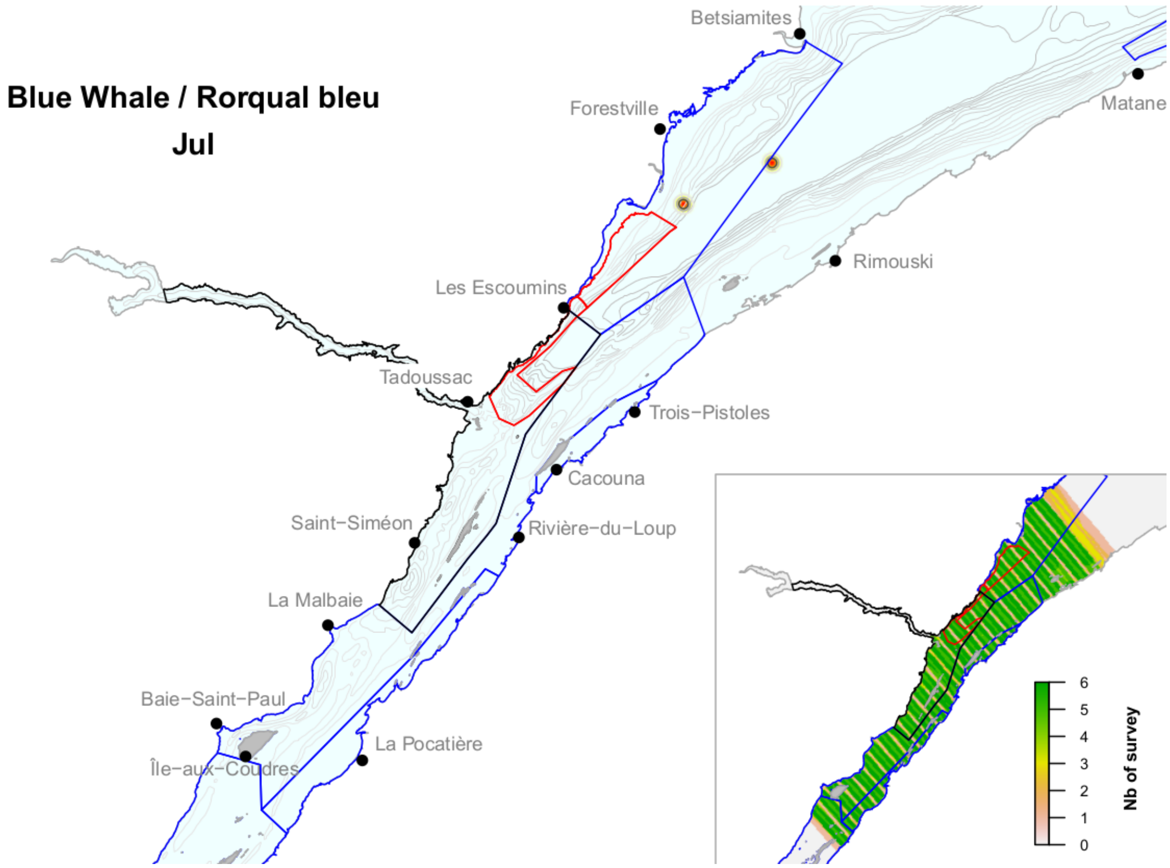
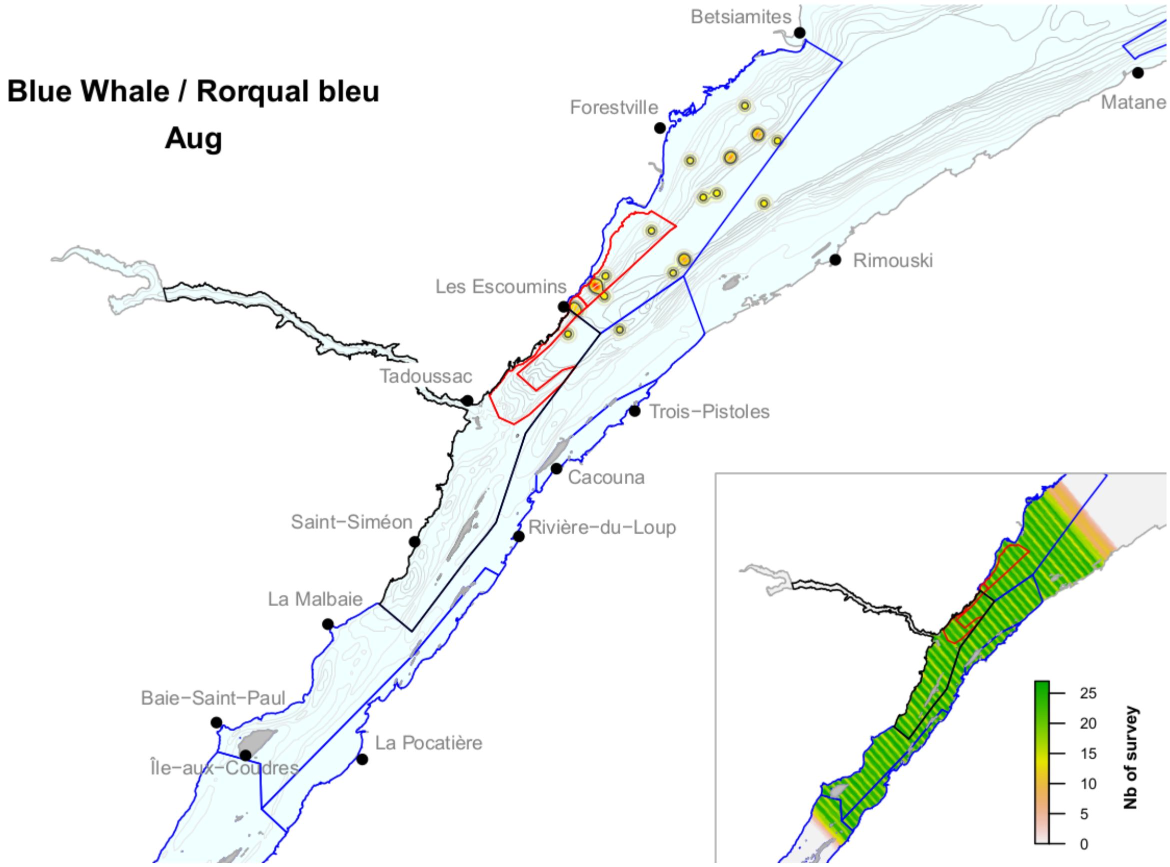


Appendix 17. Kernel representation of the monthly distribution of blue whale observations and observation effort in the St. Lawrence estuary based on the Cetus survey program conducted between 2001 and 2016. Note: This map covers the zone from Ile-Aux-Coudres to Forestville-Rimouski including the most intensive observation effort. See the complementary maps (Appendix 14) covering Forestville-Rimouski to the downstream portion of the Estuary. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



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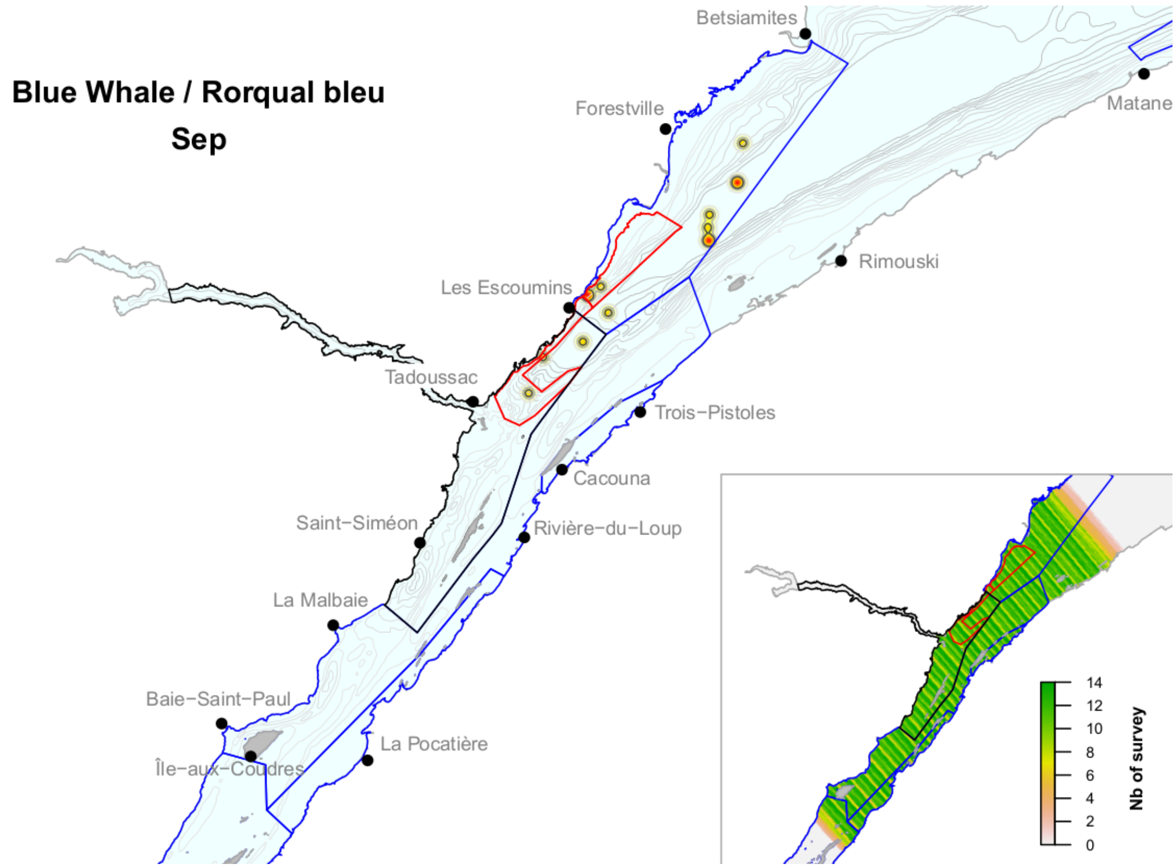
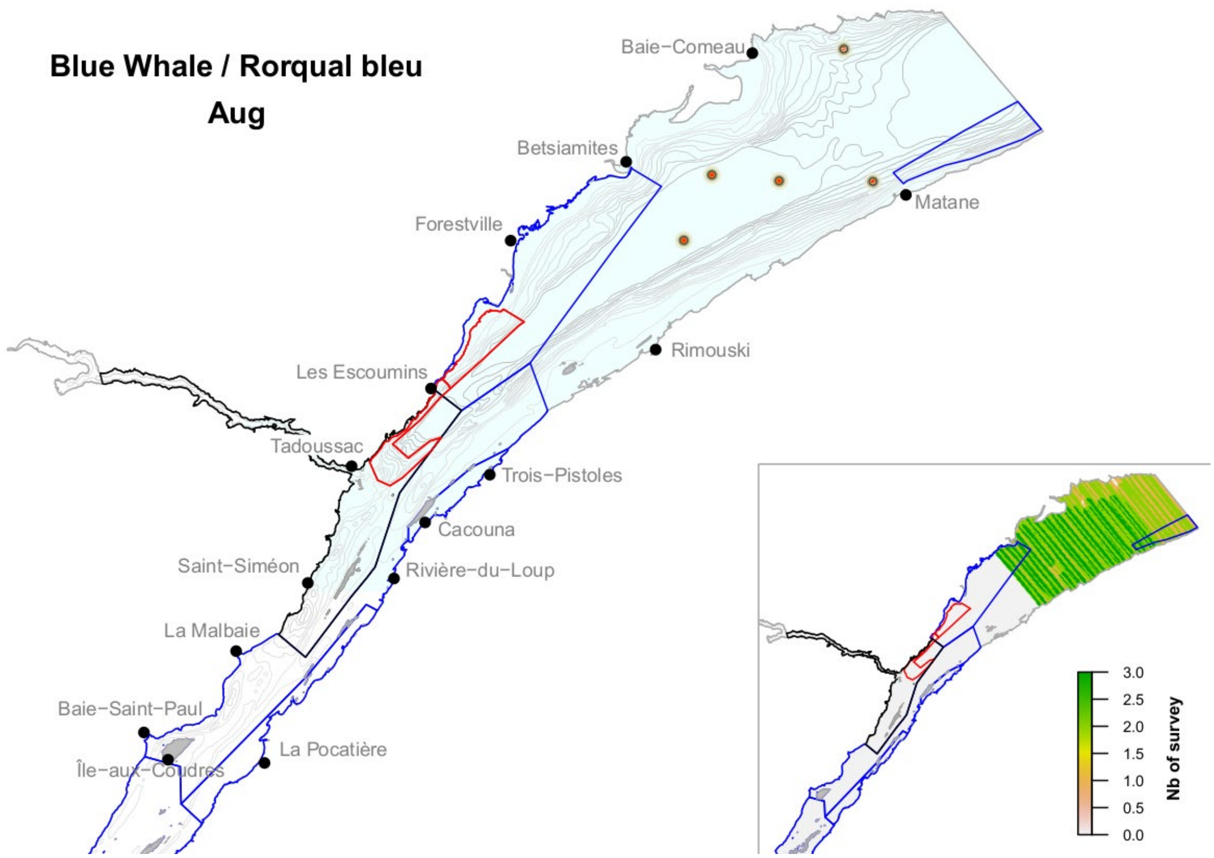
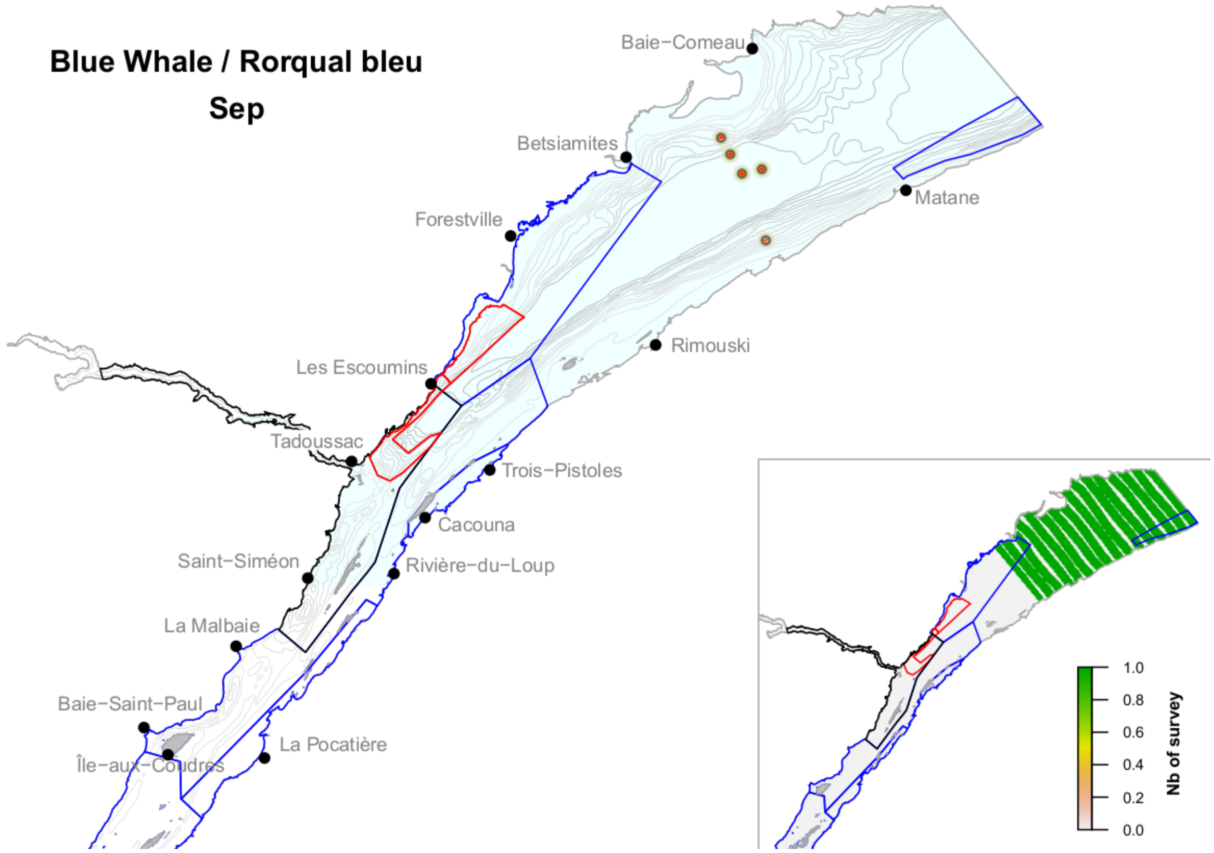


Appendix 17. Continued



Appendix 18. Kernel representation of the monthly distribution of blue whale observations and observation effort in the St. Lawrence estuary based on systematic aerial surveys conducted between 2001 and 2016. Note: This map covers the zone from Forestville-Rimouski to the downstream portion of the Estuary including the less intensive observation effort. See the complementary maps (Appendix 17) covering Ile-Aux-Coudres to Forestville-Rimouski. The red polygon represents a speed limit zone including a no-go area in its eastern part. The Saguenay - St. Lawrence Marine Park is shown as a black polygon and the blue polygons delimit different areas envisioned as marine protected areas. Bathymetry is represented as grey isolines.



Appendix 18. Continued