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Monitoring of the population and contamination of the Northern Gannet in Quebec, 1966–2009

Jean-François Rail, Louise Champoux, Raphaël A. Lavoie and Gilles Chapdelaine

Quebec Region

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MONITORING OF THE POPULATION AND CONTAMINATION OF THE NORTHERN GANNET IN QUEBEC, 1966–2009

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Aerial view of Rocher aux Oiseaux, Magdalen Islands, with its Northern Gannet colony, 2009 © J.-F. Rail
Mackerel freshly regurgitated by a Northern Gannet, 2009 © J.-F. Rail
Big Northern Gannet chick with its parent, 2011 © J.-F. Rail
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ABSTRACT

Every five years, starting in 1979, the Canadian Wildlife Service has monitored the population trend of the three Northern Gannet colonies in Quebec, as well as monitoring breeding success at the largest gannet colony, which is located on Bonaventure Island. Data on diet have also been gathered in an opportunistic way at Bonaventure Island. The size of the Northern Gannet population grew constantly from 1976 to 2009, and is currently at a high level at nearly 90 000 breeding pairs. Breeding success at Bonaventure Island remained high throughout this period, except in 2009, when it fell below the threshold value required for the long-term maintenance of the colony. Mackerel is the mainstay of the diet of Northern Gannets on Bonaventure Island, but Capelin and herring can be important early and late in the breeding period, as important seasonal variations are observed. Since 1969, Northern Gannet eggs from Bonaventure Island have been collected to monitor levels of contaminants. Levels of *p,p'*-DDE, which caused low breeding success in Bonaventure Island gannets from 1966 to 1974, decreased by 99.4% from 1969 to 2009 (17.1 to 0.1 mg/kg ww). PCBs and most organochlorines also showed decreasing trends. Dioxins, furans and non-ortho PCBs, as well as brominated flame retardants (BFRs), were measured in 2004 and 2009 only. The sum of dioxins and furans was significantly lower in 2009 than in 2004, while the sum of BFRs, although lower in 2009 than in 2004, was not significantly different. Mercury decreased by 56% between 1969 and 2009 (0.45 to 0.20 mg/kg ww). No temporal trends were observed in carbon (corrected for the Suess effect) and nitrogen stable isotopes in gannet eggs. Hence it does not seem that either trophic level or foraging area had any influence on concentrations of contaminants. The population of Northern Gannets in Quebec appears healthy at present, but many factors that could potentially affect the population trend in the near future (habitat availability, changes in ocean conditions, climatic extremes, distribution and abundance of prey, emerging contaminants, etc.) are discussed.

RÉSUMÉ

Le Service canadien de la faune fait un suivi quinquennal de la tendance de la population de Fous de Bassan aux trois colonies québécoises depuis 1979, en plus de mesurer le succès reproducteur à l'une de celles-ci, soit l'île Bonaventure. Des données sur le régime alimentaire ont aussi été amassées de façon opportuniste à l'île Bonaventure. Les effectifs de la population de Fous de Bassan au Québec n'ont cessé de croître entre 1976 et 2009, et sont actuellement à un haut niveau, soit tout près de 90 000 couples. Le succès reproducteur à l'île Bonaventure est demeuré élevé durant cette période, sauf en 2009 où il a chuté sous le seuil nécessaire pour que la colonie se maintienne à long terme. Le maquereau domine le régime alimentaire du Fou de Bassan à l'île Bonaventure, mais on observe d'importantes variations saisonnières qui font que le capelan et le hareng peuvent aussi être importants tôt ou tard en saison. Depuis 1969, des œufs de Fous de Bassan de l'île Bonaventure ont été récoltés pour faire le suivi de leur contamination. Les concentrations de *p,p'*-DDE, qui ont entraîné un faible succès de reproduction des fous de l'île Bonaventure de 1966 à 1974, ont diminué de 99,4 % de 1969 à 2009 [de 17,1 à 0,1 mg/kg poids frais (pf)]. Les BPC et la majorité des organochlorés montrent également des tendances décroissantes. Les dioxines, les furannes et les non-ortho-BPC, de même que les produits ignifuges bromés (PIB), n'ont été mesurés qu'en 2004 et 2009. La somme des dioxines et des furannes était significativement plus faible en 2009 qu'en 2004, tandis que les PIB, bien que plus faibles en 2009 qu'en 2004, n'étaient pas significativement différents. Le mercure a diminué de 56 % entre 1969 et 2009 (de 0,45 à 0,20 mg/kg pf). Aucune tendance temporelle des niveaux des isotopes stables de carbone (corrigé pour l'effet Suess) et d'azote n'a été observée. Par conséquent, il semble que ni le niveau trophique ni le lieu d'alimentation n'ont une influence sur les concentrations de contaminants. La population de Fous de Bassan apparaît en bonne santé au Québec, mais différents facteurs ayant le potentiel d'affecter la tendance de la population dans un proche avenir (disponibilité d'habitat, changements océanographiques, extrêmes climatiques, abondance et répartition des poissons pélagiques, contaminants émergents, etc.) sont abordés.

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1 INTRODUCTION

The Northern Gannet (*Morus bassanus*) population of the Gulf of St. Lawrence, which consists of 3 colonies—Bonaventure Island, Bird Rocks (Magdalen Islands) and Falaise aux Goélands (Anticosti Island)—accounts for more than 75% of the total North American gannet population. Besides the three colonies in the Gulf, there are 3 other colonies along the east coast of Newfoundland, specifically on Funk and Baccalieu islands, and at Cape St. Mary's (Nettleship and Chapdelaine 1988). Since 1984, the Quebec and Atlantic regions (Chardine 2000) of the Canadian Wildlife Service (CWS) have been jointly conducting a census of all the Northern Gannet colonies in North America.

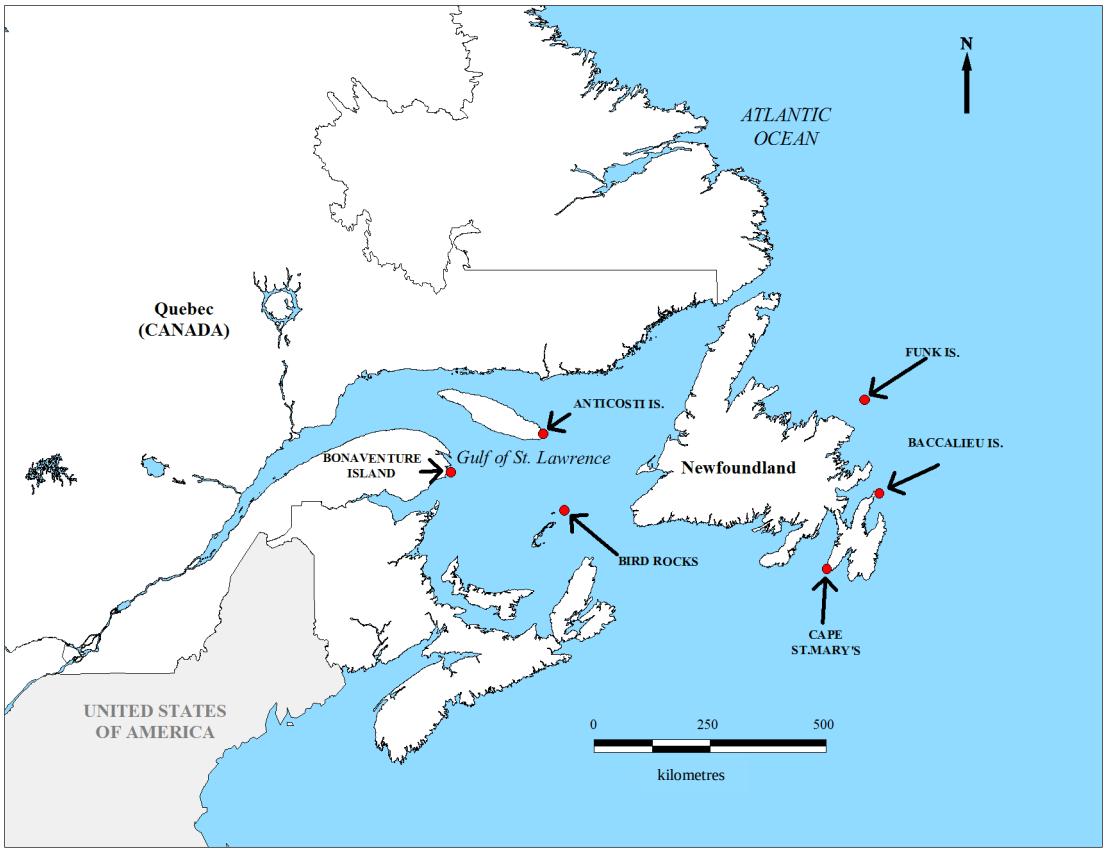

Figure 1. Location of the six North American Northern Gannet colonies.

Although estimates are available from as far back as 1860 (Bryant 1861), it was not until 1969 that more reliable estimates of the size of the Gulf of St. Lawrence colonies were obtained from aerial photographs, the original proofs of which are archived at the CWS – Quebec Region. Other reproduction-related data for Bonaventure Island was collected by Poulin (1968), Lafleur (1969), Turgeon (1971), and Taylor and Nettleship (1974). In 1979, in an extension of this work, the CWS undertook monitoring at the Bonaventure Island colony based on a five-year cycle, to track Northern Gannet hatching success, fledging success and net productivity, which are important parameters for understanding population dynamics (Chapdelaine 1977). The Northern Gannet (at Bonaventure Island) was subsequently chosen as a sentinel species or bioindicator for the state of the Gulf of St. Lawrence, under the State of the St. Lawrence Monitoring Program (Painchaud and Villeneuve 2003). Bonaventure Island is an exceptional site for conducting research on this species (Rail 2009).

In addition, the Ecotoxicology and Wildlife Health Division of the Wildlife and Landscape Science Directorate (formerly the Wildlife Toxicology Program of the CWS) has collected Northern Gannet eggs on Bonaventure Island since 1968 to measure the concentrations of various contaminants. The results of the monitoring of population size, breeding success and contaminants conducted between 1968 and 1984 are discussed in Nettleship and Chapdelaine (1988), Chapdelaine et al. (1987) and Elliott et al. (1988).

Based on the results of these analyses, a causal relationship was established between the high levels of *p,p*'-DDE (degradation product of dichlorodiphenyltrichloroethane, or DDT) in eggs and eggshell thinning, low egg hatching success and consequently low breeding success, as well as the population decline observed between 1969 and 1976 (Chapdelaine et al. 1987). DDT is a synthetic insecticide that was used in agriculture and to control mosquito-borne diseases in tropical regions. In Canada, it was used for Spruce Budworm (*Choristoneura fumiferana*) control in the 1950s and 1960s (Nigam 1975). Most uses of DDT were banned in Canada in 1974, but the remaining stocks could still be used until 1990 (Environment Canada 2005). Although prohibited in North America, Europe and a number of other countries, DDT is still being used in Asia, Africa, Central America and South America, partly to control insect vectors of malaria and typhus. The DDE that is present in our environment comes from two sources: past DDT use in agriculture and atmospheric transport from other regions.

Organohalogen contaminants like polychlorinated biphenyls (PCBs), organochlorine pesticides such as *p,p*'-DDE, brominated flame retardants (BFRs) and mercury are known for their biomagnification potential (increase in concentration with increasing trophic level), their bioaccumulation potential (increase in concentration in a living organism over time) and their toxicity (Blus 2011; Fisk et al. 2001;

Harris and Elliott 2011; Lavoie et al. 2010; Pereira et al. 2009; Shore et al. 2011; Yu et al. 2009). Although the production and use of a number of these persistent toxic substances has ceased or is now regulated in many countries, they are still present in ecosystems around the world (Crosse et al. 2012; Gauthier et al. 2008; Pereira et al. 2009). Piscivorous waterbirds at higher levels of the food chain are likely to accumulate elevated concentrations of lipid-soluble contaminants, which are transferred from the female parent to her young during egg-laying. These birds are therefore good spatiotemporal bioindicators for the persistent pollutants that are present in their environment.

Although contaminants have been identified as major stressors that can affect seabird reproduction, other factors may also influence breeding success. For example, in a context where the fishing industry is grappling with declines in the stocks of some fish species, it is important to consider the abundance and quality of the prey available to a piscivorous bird species like the Northern Gannet. Monitoring their diet could help to determine the relationship between changes in diet composition and reproduction. To this end, we conducted a detailed analysis of the diet of the Northern Gannets at the Bonaventure Island colony during the summers of 2004, 2005 and 2009, and we compared the results with previously compiled data that were more sporadic (1995, 1999, 2003 and 2007).

The objective of the present technical report is to review the monitoring results for the Northern Gannet population breeding in the Gulf of St. Lawrence using the surveys of the Quebec population conducted every five years up to 2009. More specifically, for Bonaventure Island, the objectives were also to assess 1) productivity (reproductive success) and diet, particularly based on the recent results from 2004, 2005 and 2009; 2) the levels and trends of toxic substances measured in eggs from Bonaventure Island, including mercury (Hg), DDT and other organochlorine pesticides, PCBs and, more recently, dioxins, furans and brominated flame retardants; and 3) changes in stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope values in an effort to explain contaminant trends and dietary changes. The contaminant data for the period 1969 to 1984 have already been presented in Chapdelaine et al. (1987) and Elliott et al. (1988), but are used here again with new data from 1989 to 2009 for the temporal trend analyses.

2 METHODS

2.1 ESTIMATION OF THE QUEBEC POPULATION

The methodology used to estimate the number of breeding Northern Gannets has varied little between surveys, and is described in a technical report on the 1999 census (Chardine 2000). The census method, which has used digital photography since 2004, is briefly described below.

The goal of each census is to obtain an estimate of the breeding population size. This is done by counting the number of nests or, more specifically, the number of apparently occupied territories (AOTs) on aerial photographs. This distinction is important, because the nests are not usually visible on photographs, since the incubating birds cover the nests completely or almost completely. However, it is fairly easy to delineate on photos the areas where the birds are attempting to nest at the time the photographs are taken, because the territories are very evenly distributed, nest sites spaced about 80 cm apart (Poulin 1968; Appendix 1). Therefore, every bird in its AOT is counted as a nest, and when two gannets are identified close together on a photograph, it can be assumed that they are the two members of a pair present in a single AOT (Appendix 1). In short, the number of AOTs is used to estimate breeding population size; non-breeding birds that are present on the edge of the colony (mostly sub-adults called prospectors) are not counted (Appendix 1).

Photographs are traditionally taken from a small airplane (Britten Norman Islander 9-passenger aircraft) that remains a certain distance from the colony, partly to avoid disturbing the birds and partly to obtain a good overview of the colony. The number of photos taken and the airplane's position relative to the colony depend on colony size and the local topography. On Anticosti Island, gannets nest in the upper portion of cliffs in 3 or 4 small groups that need to be photographed separately. The Bonaventure Island colony covers an area of more than 1500 m, extending up the entire cliff face (nearly 100 m) and on the island plateau. The best results are obtained by first flying along the contours of the island at an altitude of about 100 m, to take a series of slightly overlapping shots of just the cliff face. A second pass is flown at an altitude of 250 m to obtain overlapping vertical shots of the birds on the plateau. It may take up to 25 photographs per pass (cliff/plateau) to cover the entire colony. The colony on Bird Rocks (Magdalen Islands) presents the same challenge as Bonaventure Island since it has both cliff and plateau sites, but it encompasses a smaller area and the plateau of the main island (barely 300 m long) can be suitably covered with just a few photographs.

The actual count is performed directly on the photographs, either on a computer in the case of digital photographs (Canon 10D camera used in 2004; Canon 5D Mark II in 2009), or on transparencies overlaid on enlargements of traditional photographs (taken with a Pentax 6×7 camera, with large format negatives, i.e., 69 × 54 mm, during previous surveys). For digital photographs Photoshop CS6 is used, whereby a new layer is created over the photo and the pencil tool is used to mark each nest (or AOT) with a dot that is a fixed number of pixels in size (e.g., 9 pixels if the diameter of the dot is set to 3) and in a color that contrasts with the photograph (e.g., bright red, see Appendix 1). After all the AOTs have been marked with a dot, Photoshop's histogram function is used to count the number of pixels of that color (on the overlay only). The result is then divided by the number of pixels per dot to obtain the number of AOTs (for more details, see Appendix 2). In the case of transparencies overlaid on enlargements of 20 × 25 cm (or larger), a counter is used following the same principle. This small electrical instrument consists of a pencil connected to a counting device (Appendix 3). When the tip of the pencil is pressed on the transparency at the location of an AOT, a click is heard and a one (1) is added to the total displayed, plus a small mark is made on the transparency to indicate that the nest has been counted. A binocular microscope is required because the birds and nests appear very small to the naked eye, even on the enlargements (Appendix 3).

2.2 PRODUCTIVITY ON BONAVENTURE ISLAND

The reproductive success of Northern Gannets on Bonaventure Island was evaluated by making at least three visits to the colony to check the contents of a few hundred nests (see Chapdelaine 1977; Chapdelaine et al. 1987; Mousseau 1984). During the first visit in late May, that is, after the breeding pairs had settled in and egg-laying was almost complete, photographs were taken of groups of nests with each group comprising a sample plot. These photos were printed and, for each group, each nest was then numbered on the photo. The exact location of where each photo was taken was recorded carefully. These sample plots were distributed in different areas of the colony, both on the plateau and on the cliff face (Appendix 4) and essentially the same sample plots were monitored every five years. The nest contents were checked when the parents briefly interrupted their brooding. On subsequent visits (in July and August), each nest was examined (from the vantage point where the photo was taken) to see whether an egg had been laid and whether it had hatched. On the last visit, in early September, the surviving chicks were fairly large and sturdy; hence it could be assumed that their parents had raised a chick that would successfully fledge. Hatching success was estimated by dividing the number of nests found to contain a chick by the original number of nests with an egg. Fledging success was the proportion of chicks that survived until the last visit. Finally, net productivity was calculated as the product of these two values, or the proportion of nests with an egg that produced a fledged chick. In addition to the monitoring done

every five years between 1979 and 2009, reproductive success was also evaluated in 2005 in parallel with the diet study. In this report, we analyze the trend in breeding success over time, and provide detailed results for the last three estimates, that is, those of 2004, 2005 and 2009.

In 2004, 584 nests distributed in 8 sample plots were studied, including 6 on the plateau and 2 on the cliff face (subcolonies A to H), to assess the different components of reproductive success of Northern Gannets at the Bonaventure Island colony. Sampling of breeding success in 2005 was very similar to the sampling done the previous year, with 534 nests distributed in approximately the same 8 sample plots. In 2009, reproductive success was evaluated the same way, by monitoring a total of 460 nests distributed in 8 sample plots. However, sample plot B was abandoned and replaced with another group of nests called B2, likewise on the plateau but farther north where there was a better vantage point, making it easier to locate and observe the nests. It should be noted that, because of a time shortage caused by poor weather conditions, the field team had to reduce the number of nests monitored in sample plot D.

2.3 GANNET DIET ON BONAVENTURE ISLAND

It is easy to study the diet of Northern Gannets by exploiting the fact that they feed their young regurgitated food (see Appendix 5), and that they are prone to spontaneously regurgitate their food when disturbed. Therefore, by walking very slowly on the edge of the colony, close enough to the first row of nests to make the nesting birds nervous, but far enough away to avoid scaring them from their nests, a researcher can collect some fresh regurgitations. The regurgitated food is from breeding adults or their young, but it may also be from non-breeding gannets (prospectors) that frequent the periphery of the colony; these birds will keep moving farther away as the researcher approaches them. The regurgitated food is collected (the contents generally consist of one or two partially digested fish [see Appendix 5]), and the different types of prey are weighed and counted.

The Canadian Wildlife Service sampled the diet of Northern Gannets on Bonaventure Island in an opportunistic manner in 1995, 1999, 2003, 2007 and 2009 (Appendix 6). On each occasion, sampling was conducted over a very limited period of 1 to 6 days, and most often between August 15 and September 1. A more comprehensive sampling was done in 2004 and 2005, which provided a more effective coverage of the chick-rearing period. In 2004 and 2005, Bonaventure Island was visited during four different periods between July 9 and September 9.

2.4 CHEMICAL ANALYSES OF CONTAMINANTS AT BONAVENTURE ISLAND

2.4.1 Sample collection and preparation

Since 1968, gannet eggs have been collected periodically from active nests on Bonaventure Island to carry out contaminant analyses. Intensive sampling of fresh and addled (unhatched) eggs was conducted for DDT analyses in 1968 (8 fresh eggs, 3 addled), 1969 (9 fresh eggs, 10 addled), 1970 (6 addled eggs), 1973 (10 fresh eggs) and 1974 (20 fresh eggs, 10 addled). Only the fresh eggs were used in the present study. In 1976, 1984 and 1989, 6 eggs were collected. Since 1994, 15 eggs have been collected every 5 years into 3 groups of 5 eggs each for the contaminant analyses. The eggs were stored at a cool temperature on-site and then sent to the National Wildlife Research Centre (NWRC) in Ottawa, Ontario, for sample preparation and chemical analysis. The contents of the eggs were homogenized and transferred to acetone-hexane-rinsed glass jars and stored at -40°C for the analyses of organohalogen contaminants or transferred to nitric acid-rinsed polyethylene containers for the analysis of mercury and other inorganic elements. Since 1994, eggshell thickness has been measured at 5 different locations on the dried shell, using an Ames no. 25 ME micrometer. Measurements from previous years were extracted from a figure given in Elliott et al. (1988) using the Data Grabber program (Roxburgh 2006). Eggshell thickness measurements corresponding to the pre-industrial era (before 1947) come from museum specimens collected in 1877, 1886, 1903 and 1915 (n = 8) in the Gulf of St. Lawrence (Elliott et al. 1988).

Although mercury in eggs has been analyzed only since 1994, archived samples of eggs can be obtained from the NWRC's specimen bank. A total of 30 samples, specifically 6 eggs from 5 different years, were selected from the list of archived samples, and retrospective mercury analyses were performed on individual egg samples from 1969 to 1989. By contrast, the analyses of eggs from 1994, 1999, 2004 and 2009 were performed on 3 composite samples made up of 5 eggs per year. Although eggs were analyzed for total PCBs from 1968 to 2009, the analysis of congeners began in 1989. Organochlorine pesticides were measured in eggs from 1968 to 2009, and analyses of polybrominated diphenyl ethers and dioxins and furans were conducted in 2004 and 2009. Manganese (Mn), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), rubidium (Rb), cadmium (Cd) and lead (Pb) were not measured in gannet eggs until 2009.

2.4.2 Mercury and other inorganic elements

Mercury analysis in the eggs was carried out at the NWRC's laboratory. The homogenized egg contents were first freeze-dried to determine the moisture content. Total mercury was determined by either of two methods, depending on the period of analysis. In 1994 and 1999, following acid digestion of the samples, mercury was analyzed by cold vapour atomic absorption spectrometry, using a Perkin Elmer

3030B AAS atomic absorption spectrometer equipped with a Varian VGA-76 hydride generator and a Varian PSC-55 autosampler (Neugebauer et al. 2000). The detection limit was 0.01 mg/kg dry weight (dw). For the retrospective analyses (1969–1989) as well as for 2004 and 2009, total mercury was determined without prior acid digestion by atomic absorption spectrometry on an Advanced Mercury Analyzer (AMA-254, ALTEC) equipped with an ASS-254 autosampler (ALTEC), which employs direct combustion of the sample in an oxygen-rich atmosphere (Neugebauer et al. 2000). For the samples in the retrospective analysis and those for 2004, the accuracy of the analyses was determined by using certified reference materials DOLT-2 and DORM-2 obtained from the National Research Council of Canada (NRC, Ottawa, Canada). Some randomly selected samples were also analyzed in duplicate. The detection limit was 0.09 mg/kg dw and 0.05 mg/kg dw for the retrospective analysis and the 2004 analysis, respectively. In 2009, the accuracy of the method was determined by analyzing the concentration of reference materials DOLT-3 and TORT-2 from the NRC and 1566b from the National Institute of Standards and Technology (NIST) in the United States, as well as ERM-CE278 and BCR-463 from the Institute for Reference Materials and Measurements (IRMM) of the European Commission. The detection limit was 0.006 mg/kg dw. The results showed that there were no significant differences between the two methods and that recovery ranged from 89.8 to 113.1%, which is within certified limits. The concentrations are reported in wet weight, since there was no significant difference in egg moisture content among years (ANOVA: $F_{8, 33} = 0.5$; $p = 0.842$).

The NWRC conducted the analysis of inorganic elements by inductively coupled plasma-mass spectrometry (ELAN 9000, Perkin-Elmer) using the method described in the procedure MET-CHEM-ICP-01A (Environment Canada, available on request) with modifications for biological samples for EPA method 200.8 (U.S. Environmental Protection Agency). The samples were freeze-dried and then digested with nitric acid at 100°C for 4 h. The accuracy of the method was determined by analyzing the concentration of reference materials DOLT-3 and TORT-2 (CNRC) as well as 1566b (NIST). Recovery of metals from the reference materials ranged from 79.1 to 109.9%, which is within acceptable limits. The practical quantitation level (PQL = 5 × the detection limit; in mg/kg dw) is given in Table 11.

2.4.3 Polychlorinated biphenyls, organochlorine pesticides and brominated flame retardants

Until 1984, polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCs) were determined by gas chromatography with an electron capture detector (GC/ECD) using packed columns. Total PCBs were expressed as equivalent to a 1:1 mixture of Aroclor 1254 and Aroclor 1260 (hereafter PCB 1:1). In subsequent analyses, replacement of these columns with glass capillary columns permitted the identification of 42 distinct congeners. Although this method made it possible to separate out the main organochlorine

compounds and PCB congeners, after the sample was separated into 3 fractions, some congeners could not be separated and identified correctly. Since 1997, the analyses have been performed with a quadrupole mass spectrometer coupled with gas chromatography (GC/MSD) operated in selected ion monitoring mode, which permits the identification of a larger number of compounds (67 PCB congeners versus 42). The method used by the NWRC to analyze PCBs and OCs from 1969 to 1994 is as described in Norstrom and Won (1985); the analyses performed from 1997 to 2004 used CWS method no. MET-CHEM-OC-04 as described in Won et al. (2001); and the analyses performed in 2009 used CWS method no. MET-CHEM-OC-06B (Environment Canada, available on request). First, the lipids were extracted from the eggs with a dichloromethane/hexane (1:1) mixture. Then, the chemical substances of interest were extracted and separated from the lipids and biogenic compounds by gel permeation chromatography (GPC). The extracts obtained were then purified by Florisil column chromatography and finally analyzed by GC/ECD (prior to 1997; Hewlett-Packard 5840GC equipped with an HP 7673A autosampler) or by GC/MSD (in 1999, Hewlett-Packard 5890 Series II connected to an HP 5970; in 2004 and 2009, Agilent 6890N connected to an Agilent 5973N). The organochlorine pesticides of interest were 1,2,4,5- and 1,2,3,4-tetrachlorobenzene, pentachlorobenzene, hexachlorobenzene (HCB), α-, β-, and γ-hexachlorocyclohexane (HCH), octachlorostyrene (OCS), heptachlor epoxide, oxychlordane, *trans*- and *cis*-chlordane, *trans*- and *cis*-nonachlor, *p,p'*-DDD, *p,p'*-DDE, *p,p'*-DDT, dieldrin, mirex, photo-mirex and tris (4-chlorophenyl) methanol (TCPM). In all, 67 congeners of PCB were analyzed and classified according to their level of chlorination (International Union of Pure and Applied Chemistry numbers; IUPAC, [Ballschmiter et al. 1992]): trichlorobiphenyl (tri-PCB): 16/32, 17, 18, 20/33, 22, 28 and 31; tetrachlorobiphenyl (tetra-PCB): 42, 44, 47/48, 49, 52, 56/60, 64, 66, 70/76 and 74; pentachlorobiphenyl (penta-PCB): 85, 87, 90/101, 92, 95, 97, 99, 105, 110 and 118; hexachlorobiphenyl (hexa-PCB): 128, 130, 137, 138, 141, 146, 149, 151, 153, 156, 157 and 158; heptachlorobiphenyl (hepta-PCB): 170/190, 171, 172, 174, 176, 177, 178, 179, 180, 183 and 187; octachlorobiphenyl (octa-PCB): 194, 195, 196/203, 200, 201 and 202; and nonachlorobiphenyl (nona-PCB): 206, 207, 208. Three new congeners (PCB 199, 205 and 209) were added in 2009. Congeners separated by a forward slash are ones that coelute during chemical analysis; the sum of these pairs is reported. The total PCB concentration (ΣPCB) that is reported is the sum of these congeners. The congeners were also grouped according to the number of chlorine molecules (from tri-PCB to nona-PCB) and their position on the biphenyl ring (from 1-ortho to 4-ortho). However, to permit comparison, only the 38 congeners analyzed every year were taken into account when calculating the sums for total PCBs and homologue and ortho groups. The PCB 1:1 were also measured for all these years as a basis of comparison. The detection limit differed for each compound of interest but was typically lower than 0.001 mg/kg ww. The NWRC's quality control program includes the analysis of a reference material sample of known concentration. For the GC/MSD analyses, the samples were spiked with a ^{13}C-OC/PCB internal

standard. Blanks and an internal reference material (07CC) were analyzed to ensure the quality of the results. Recovery was within acceptable limits for most of the congeners except HCB (45.4 ± 7.5%) and TCPM (29.5 ± 6.4%) from 2009, for which corrected recovery values were used.

In 2004 and 2009, eggs were analyzed for brominated flame retardants (BFRs) using the method of Covaci et al. (2003). This method is similar to that used for PCBs and organochlorine pesticides (GC/MSD). The samples were spiked with BDE-30 and BDE-195 internal standards (in 2004) or BDE-30, BDE-156 and 13C-BDE-209 internal standards (in 2009), and recovery was within acceptable limits. A total of 15 congeners (IUPAC number) of polybrominated diphenyl ethers (ΣPBDE) were analyzed and grouped according to their degree of bromination following the method of Ballschmiter et al. (1992): tribromodiphenyl ether (tri-BDE): 17 and 28; tetrabromodiphenyl ether (tetra-BDE): 47, 49 and 66; pentabromodiphenyl ether (penta-BDE): 85, 99, 100 and 101; hexabromodiphenyl ether (hexa-BDE): 138, 153 and 154 (coeluted with brominobiphenyl-153, BB-153); heptabromodiphenyl ether (hepta-BDE): 183 and 190; and decabromodiphenyl ether (deca-BDE): 209. Other brominated flame retardants (BFRs) such as BB-153 (coeluted with BDE-154) and hexabromocyclododecane (HBCDD) were also quantified and grouped with hepta-BDE. In 2009, 6 new compounds (α-TBECH, HBB, BB-101, BTBPE, syn-DP and anti-DP) were analyzed, but they were excluded from the temporal trend analysis because most of them fell below the detection limit or because they overestimated the totals for 2009 relative to 2004. The BFR data were corrected for percent recovery and for the values of blanks. The detection limit was 0.1 μg/kg ww.

2.4.4 Dioxins and furans

The polychlorodibenzo-*p*-dioxins (dioxins), polychlorodibenzofurans (furans) and non-ortho PCBs were analyzed in the eggs from 2004 and 2009 by the RPC Laboratory (Fredericton, NB), using a method similar to that of Simon and Wakeford (2000) based on U.S. EPA methods 1613B and 8290A and described in Braune et al. (2007). Briefly, the samples were mixed with anhydrous sodium sulphate, transferred to a chromatography column and extracted with solvent. The extracts were then cleaned up by gel permeation chromatography and separated on a carbon/fibreglass column. The samples were spiked with a solution containing two PCDD compounds and four non-ortho PCBs. Samples were analyzed in duplicate; blanks, certified samples and reference materials were also analyzed. Most of the results were within the acceptable range (40–120%). The analysis was performed using a high-resolution double-focusing mass spectrometer (VG Autospec Ultimate) coupled to a high-resolution gas chromatograph (HP 5890 series II). The results were corrected for standards recovery. The detection limit for each compound generally ranged from 0.1 to 1.0 ng/kg ww.

2.5 STABLE ISOTOPES ON BONAVENTURE ISLAND

To determine whether dietary changes occurred over the study period, stable isotopes of nitrogen (δ^{15}N) and carbon (δ^{13}C) were measured in the gannet eggs. The δ^{15}N and δ^{13}C values were used to determine the trophic level of the gannets and the origin of their prey items, respectively. A known mass of sample (1 ± 0.2 mg) was weighed in a tin capsule on a microbalance (±0.001 mg). For the samples from 1968 to 2004, the concentration and the organic carbon and nitrogen isotope composition were measured in the laboratory at Environment Canada's National Hydrology Research Centre (Saskatoon, Sask.) by flash combustion at 1800°C in a Robo Prep elemental analyzer, and the resultant CO_2 and N_2 gases were analyzed using an interfaced Europa 20:20 continuous-flow isotope-ratio mass spectrometer (CF-IRMS). The samples from 2009 were analyzed by the G.G. Hatch Stable Isotope Laboratory in the Faculty of Science, Department of Earth Sciences, University of Ottawa, by flash combustion using a Vario EL III element analyzer (Elementar, Germany), and the resultant CO_2 and N_2 gases were analyzed using a CF-IRMS Delta XP Plus Advantage (Thermo, Germany). The stable isotope ratios were quantified as the deviation in parts per thousand (‰) of the isotope ratio in the sample from standard reference materials and expressed in δ notation by

$$\delta X = [(R_{sample} / R_{standard}) - 1] \times 1000 \qquad (1)$$

where X is ^{13}C or ^{15}N and R is the corresponding ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$. R standard values were PeeDee Belemnite (PDB) for carbon, and atmospheric N_2 (air) for nitrogen. Based on replicate measurements of laboratory internal standards, measurement precision was estimated to be 0.2‰.

2.6 STATISTICAL ANALYSES AND CALCULATIONS

Chemical analyses were performed on at least six eggs individually from 1968 to 1989, and on three composite samples consisting of five eggs subsequently. In order to ensure homogeneity of variance, which is an essential condition for statistical analyses, five eggs were randomly selected out of the six eggs for each year from 1968 to 1989, and the mean was calculated for each year. Therefore, each sample represents five eggs, either as a mean or a composite sample. The concentrations of the contaminants are reported in mg/kg ww for OCs, PCBs and mercury; in mg/kg dw for inorganic elements; in µg/kg ww for BFRs; and in ng/kg ww for dioxins and furans. The lipid content and moisture content are provided to permit conversion to lipid weight and dry weight.

For the PCB and OC analyses, large differences were found in the amounts of the different congeners and compounds detected by the two methods (ECD and MSD). The correction method described in de Solla et al. (2010) was applied to the gannet data, by using the difference in the mean

concentrations of reference materials analyzed by the ECD and MSD methods (*diff*) to adjust all the results of the ECD analyses (ECD_{adj}). Since the data and reference material described in de Solla et al. (2010) came from the NWRC laboratory, we felt that their method should be applicable to our data as well. The 1968 data could not be corrected and so were eliminated from the analyses. The equations below describe the calculations performed.

$$diff = \frac{(MSD - ECD)}{ECD} \quad (2)$$

$$[ECD]_{adj} = [ECD] + (diff) \times [ECD] \quad (3)$$

The concentrations of the PCB congeners and the organochlorine compounds in the reference materials analyzed by MSD were 62% lower to 337% higher than those measured by ECD. Total PCBs and PCB 1:1 were 24% and 5% higher when analyzed by MSD versus ECD. The contaminants showing the largest absolute differences were those with the lowest concentrations, near the detection limits. In the gannet egg samples, the corrected ΣPCB (all congeners), ΣPCB_{38} (38 congeners) and PCB 1:1 values in 1989 and 1994 were, respectively, 37%, 17% and 6% higher than the uncorrected values. The corrected OC values from 1969 to 1994 were 6.5% lower on average than the uncorrected values. The corrections had very little effect on the temporal trend analyses of the contaminants.

The data falling below the detection limits were estimated by dividing the value of the detection limit by two. Contaminants for which more than 50% of the values were below the detection limits were excluded from the analyses. The data were checked for normality and homogeneity of variance before the statistical analyses were performed. Variables that were not normally distributed were log-transformed (base 10). Analyses of variance followed by a Tukey test were used to examine the differences in concentrations among years, and linear regression was used to examine the temporal changes in concentrations. In the case of PCBs and BFRs, in order to have comparable data, only the congeners analyzed every year were considered when calculating totals and temporal trends. A Student's *t*-test was performed to compare the means of BFR concentrations and of dioxin and furan concentrations between 2004 and 2009.

To account for a possible variation in lipid content and trophic level, the temporal trends of contaminants are sometimes analyzed by multiple linear regression with the year, lipid content and $\delta^{15}N$ as independent variables (Braune 2007). However, no temporal trends were observed in lipid content ($F_{1, 18} = 4.0$; $p = 0.06$) or $\delta^{15}N$ ($F_{1, 16} = 2.2$; $p = 0.16$) for the composite samples in our study. A small proportion of the halogenated organic compounds measured in the composite samples showed significant relationships ($p < 0.05$; simple linear regressions) with lipid content (9%) and with $\delta^{15}N$ (9%). Similarly,

we found no relationship between mercury concentration and moisture content ($F_{1, 16} = 0.37$; $p = 0.55$) or $\delta^{15}N$ ($F_{1, 16} = 0.42$; $p = 0.53$). Simple linear regression was therefore used to analyze the temporal trends in contaminants. Outliers were detected using Cook's distance and excluded when they had a Cook's distance value of over 1 (Quinn and Keough 2002).

The $\delta^{13}C$ values were adjusted to take the Suess effect into account by using the post-1950 portion of the equation of Farmer and Leonard (2011):

$$\delta^{13}C_{corrected} = \delta^{13}C_{normalized} - b_{hist} \times (1950 - t_i) - b_{mod} \times (t_i - 1950) \qquad (4)$$

where b_{hist} is the historical decline in $\delta^{13}C$ (0.007‰) and b_{mod} is the annual decline modelled in North Atlantic surface waters between 1950 and 1993 (0.026‰).

The half-life of a contaminant is the time required for the concentration to decrease to 50% of its original value. The half-life of PCB congeners and organochlorines was estimated from the slope of the regression line for the relationship between time and concentration according to an exponential logarithmic function, using the following equation:

$$T_{1/2} = \frac{\ln (2)}{\text{slope}} \qquad \text{(Tardiff and Katzman 2007)} \qquad (5)$$

A toxic equivalent (TEQ) based on the relative toxicity of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin was calculated using the toxic equivalency factors (TEFs) published by Van den Berg et al. (1998) for the PCB congeners for which equivalents were available for birds, that is, mono-ortho-substituted congeners (105, 118, 156 and 157), non-ortho-PCBs (77, 81, 126 and 169), and dioxins and furans. The concentration of each congener is multiplied by its TEF, which ranges from 1 for the most toxic to 0.00001 for the least toxic. The individual toxic equivalent values are summed to give the total toxic equivalent.

A Spearman's rank correlation matrix was used to determine the relationship between the contaminants, eggshell thickness and stable isotopes. The level of significance α was adjusted with the Bonferroni correction for the number of tests performed (41 contaminants; $\alpha = 0.05 / 41 = 0.001$).

3 RESULTS

3.1 ESTIMATION OF THE QUEBEC POPULATION

On Bonaventure Island, the Northern Gannet colony contained a recently estimated 53 635 breeding pairs in 2004 and 59 586 in 2009 (Table 1). The Bird Rocks colony in the Magdalen Islands was estimated to consist of 23 461 pairs in 2004 and 30 010 pairs in 2009 (Table 2). By contrast, the Anticosti Island colony, which is very small compared to the other two, remained stable over this period, with 221 pairs in 2004 and 200 pairs in 2009.

3.1.1 Population trend

The Bonaventure Island colony showed a fairly steady increase in numbers (between 2.73 and 5.53% per year) between 1976 and 1999 (Table 1 and Figure 2). Between 1999 and 2004, the annual rate of growth reached 7.75% (9.05% on the plateau). During the five-year period from 2004 to 2009, however, the growth rate slowed to 2.13% per year. Slightly less than one third (30%) of the nests were located on the cliff face at Bonaventure Island in 2009, compared to 57% in 1969 (Table 1). This change is due to the fact that, curiously, much of the decrease observed between 1969 and 1976 (-20%) consisted of cliff ledge nests (-44%) and that, in subsequent years, on average, the rate of increase was greater on the plateau than on the cliff face.

The Bird Rocks colony exhibited essentially the same trend as the Bonaventure Island colony (Figure 2), with a decline between 1969 and 1973 (only on the cliff face; the plateau was almost deserted) and steady annual growth (between 2.07% and 11.34%) from 1976 to 2009. Whereas the rate of increase on the plateau was exceptionally high (Table 2), almost no growth occurred on the cliff face (Figure 2). The proportion of cliffside nests fell from 100% in 1973 to only 19% in 2009.

Table 1. Population trend of the Northern Gannet colony on Bonaventure Island between 1969 and 2009, according to habitat type.

Year	Cliff[1]	Annual growth rate[2]	Top plateau[1]	Annual growth rate[2]	Total population[1]	Annual growth rate[2]
1969	11 854		8 657		20 511	
		-5.95 %		-1.93 %		-4.19 %
1973	9 274		8 007		17 281	
		-10.50 %		6.79 %		-1.73 %
1976	6 649		9 751		16 400	
		1.95 %		4.73 %		3.62 %
1979	7 045		11 200		18 245	
		3.72 %		2.44 %		2.94 %
1984	8 457		12 633		21 090	
		0.58 %		4.07 %		2.73 %
1989	8 704		15 421		24 125	
		1.94 %		7.36 %		5.53 %
1994	9 580		21 994		31 574	
		6.38 %		1.66 %		3.19 %
1999	13 050		23 886		36 936	
		5.18 %		9.05 %		7.75 %
2004	16 802		36 833		53 635	
		1.36 %		2.47 %		2.13 %
2009	17 974		41 612		59 586	

[1]Estimated number of breeding pairs (or AOTs)
[2]Between two successive surveys, on the preceding column

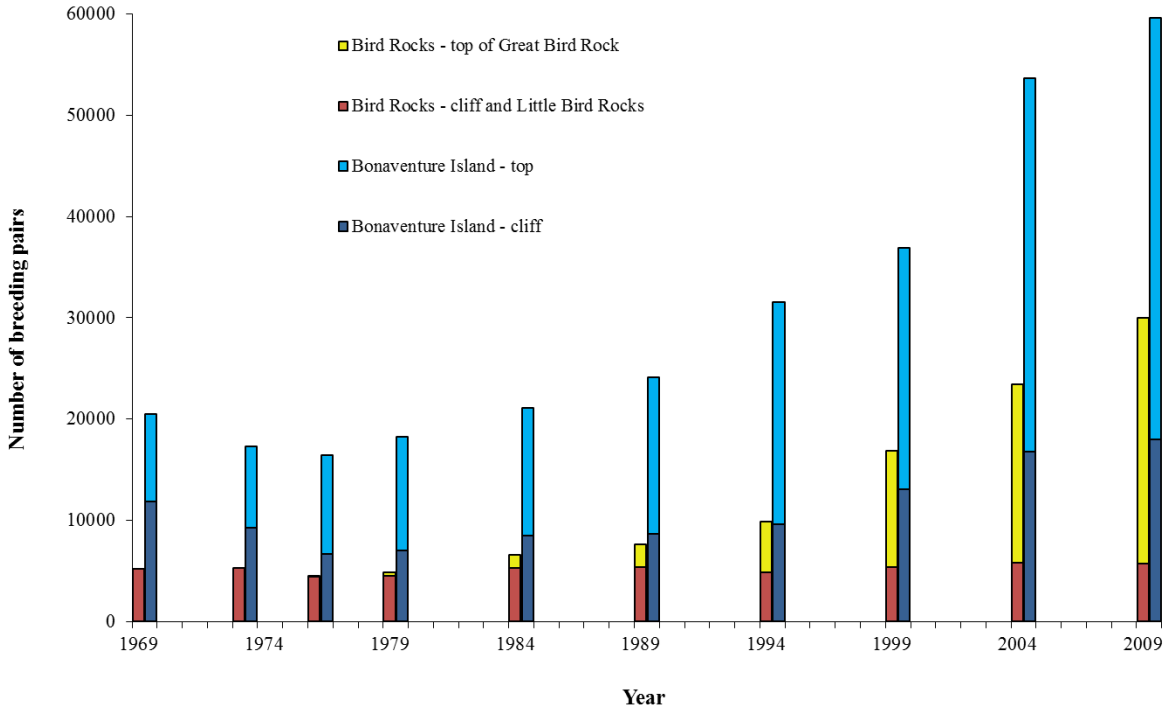

Figure 2. Population trend of Northern Gannet colonies on Bonaventure Island and Bird Rocks (Magdalen Islands), according to habitat type (cliff versus plateau).

Table 2. Population trend of the Northern Gannet colony on Bird Rocks between 1969 and 2009, according to habitat type.

Year	Cliff and Small Bird Rocks[1]	Annual growth rate[2]	Plateau of Great Bird Rock[1]	Annual growth rate[2]	Total population[1]	Annual growth rate[2]
1969	5 204		very few		5 204	
		0.60 %		≈ 0		0.60 %
1973	5 331		very few		5 331	
		-5.82 %		≈ 0		-5.12 %
1976	4 453		≈ 100		4 553	
		0.29 %		51.83 %		2.07 %
1979	4 492		≈ 350		4 842	
		3.39 %		29.65 %		6.36 %
1984	5 308		1 282		6 590	
		0.15 %		12.31 %		3.00 %
1989	5 349		2 291		7 640	
		-1.95 %		16.99 %		5.25 %
1994	4 848		5 020		9 868	
		2.08 %		18.05 %		11.34 %
1999	5 374		11 510		16 884	
		1.60 %		8.92 %		6.80 %
2004	5 819		17 642		23 461	
		-0.23 %		6.58 %		5.05 %
2009	5 753		24 257		30 010	

[1]Estimated number of breeding pairs (or AOTs)
[2]Between two successive surveys, on the preceding column

In the near future, the gannet colony at Bird Rocks could completely cover the plateau of the main island. Whether we consider the mean annual growth rate between 2004 and 2009 for the plateau (6.58%) or for the entire colony (5.05%), the number of breeding pairs can be expected to stabilize at about 47 500 in around 2018 (Figure 3 and Appendix 7).

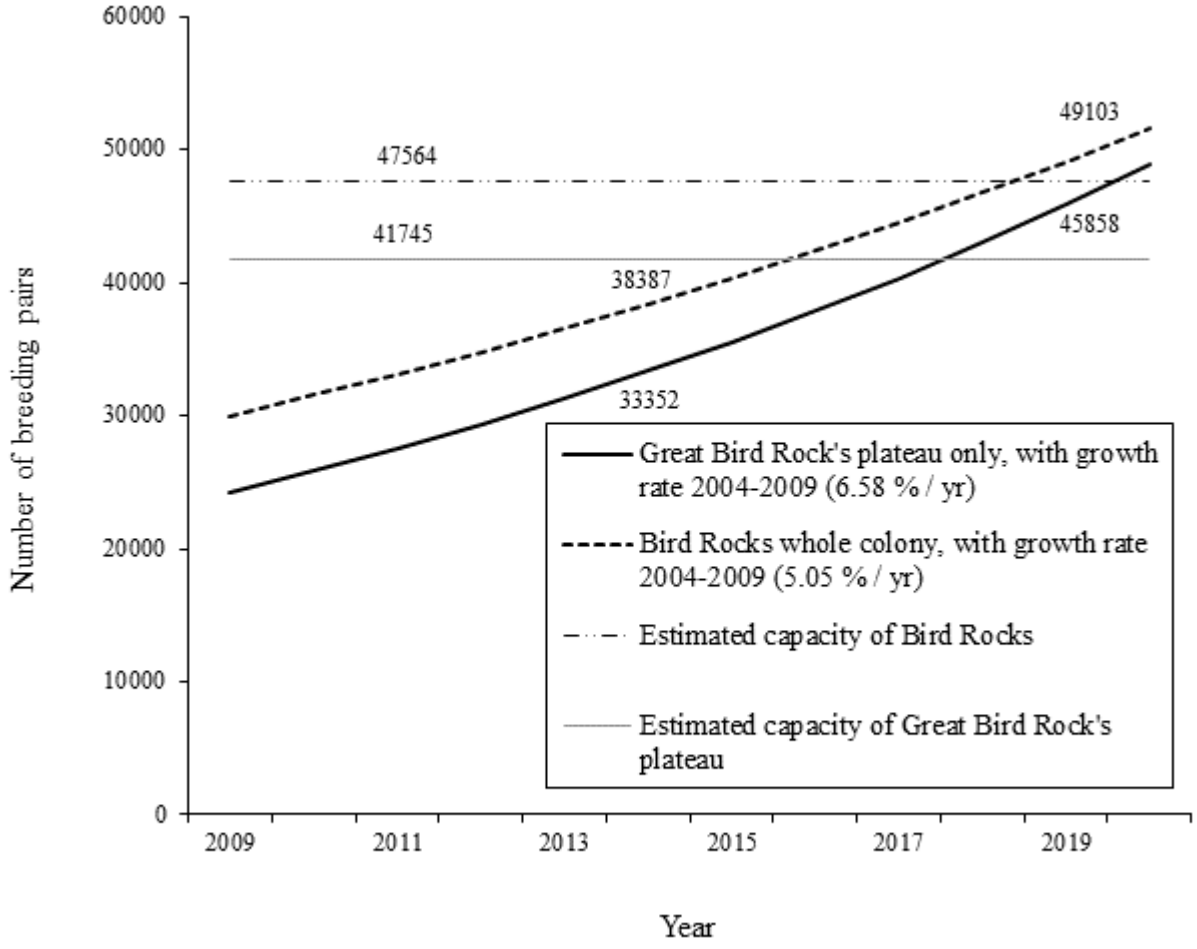

Figure 3. Demographic projection for the 2009-2020 period, at the Bird Rocks (Magdalen Islands) colony. Site capacity was determined from vacant area (not occupied by gannets) on the plateau of Great Bird Rock (see Appendix 7). Values calculated for the next census years, in 2014 and 2019, are indicated.

3.2 PRODUCTIVITY ON BONAVENTURE ISLAND

In 2004, mean net productivity at the Bonaventure Island colony was 73% (Table 3). Among subcolonies hatching success varied between 70 and 84%, while fledging success was appreciably higher, ranging from 82 to 97%. Both hatching success and fledging success were lower on average in the two cliffside subcolonies; hence net productivity was 14% lower on the cliff face than on the plateau.

Table 3. Breeding success of the Northern Gannet at Bonaventure Island in 2004.

Sub-colony	Number of eggs[1]	Number of chicks[2]	Number of fledglings[3]	Hatching success[4]	Fledging success[5]	Net productivity[6]
A (plateau)	81	68	65	84.0%	95.6%	80.2%
B (plateau)	35	26	21	74.3%	80.8%	60.0%
C (cliff)	67	47	44	70.1%	93.6%	65.7%
D (plateau)	79	65	59	82.3%	90.8%	74.7%
E (plateau)	108	87	83	80.6%	95.4%	76.9%
F (plateau)	49	37	36	75.5%	97.3%	73.5%
G (plateau)	109	89	86	81.7%	96.6%	78.9%
H (cliff)	56	39	32	69.6%	82.1%	57.1%
Total plateau	461	372	350	80.7%	94.1%	75.9%
Total cliff	123	86	76	69.9%	88.4%	61.8%
Grand total	584	458	426	78.4%	93.0%	72.9%

[1]Number of nests where an egg was laid, in the sample
[2]Number of eggs hatched, among those of the preceding column
[3]Number of juveniles present on the last visit (8 September); alive and ready to fledge
[4]Number of chicks / number of eggs in the sample
[5]Number of juveniles ready to fledge / number of chicks
[6]Number of juveniles ready to fledge / number of eggs in the sample

In 2005, hatching success ranged from 54 to 86% and fledging success, from 80 to 95% (Table 4). As expected, hatching success and fledging success were lower on the cliff face than elsewhere, except in subcolony B on the plateau where (surprisingly) hatching success was even lower. Overall, fledging and hatching success were much lower on the cliff face. Net productivity was 14.5% lower there on the cliff face, which is very similar to the situation in 2004.

Table 4. Breeding success of the Northern Gannet at Bonaventure Island in 2005.

Sub-colony	Number of eggs[1]	Number of chicks[2]	Number of fledglings[3]	Hatching success[4]	Fledging success[5]	Net productivity[6]
A (plateau)	87	74	65	85.1%	87.8%	74.7%
B (plateau)	65	35	33	53.8%	94.3%	50.8%
C (cliff)	59	40	32	67.8%	80.0%	54.2%
D (plateau)	65	54	52	83.1%	96.3%	80.0%
E (plateau)	97	75	71	77.3%	94.7%	73.2%
F (plateau)	39	28	26	71.8%	92.9%	66.7%
G (plateau)	63	54	49	85.7%	90.7%	77.8%
H (cliff)	68	45	40	66.2%	88.9%	58.8%
Total plateau	416	320	296	76.9%	92.5%	71.2%
Total cliff	127	85	72	66.9%	84.7%	56.7%
Grand total	543	405	368	74.6%	90.9%	67.8%

[1]Number of nests where an egg was laid, in the sample
[2]Number of eggs hatched, among those of the preceding column
[3]Number of juveniles present on the last visit (4-6 September); alive and ready to fledge
[4]Number of chicks / number of eggs in the sample
[5]Number of juveniles ready to fledge / number of chicks
[6]Number of juveniles ready to fledge / number of eggs in the sample

In 2009, hatching success varied considerably and was fairly low (between 36 and 70%), whereas fledging success appeared to be low in 3 sample plots and near normal (between 85 and 94%) in the other 5 plots (Table 5). As in preceding years (see also Chapdelaine et al. 1987), hatching success and fledging success were lower on the cliff face than on the plateau on average; however, the difference was even greater in 2009. Even though hatching success was abnormally low in several plots, and even lower in subcolony D on the plateau than in subcolony C on the cliff face, hatching success was 16% higher overall on the plateau than on the cliffsides. Fledging success appeared to be fairly high on the plateau except in plot F, but very low in the two cliffside plots. As a result, mean fledging success was almost 32% greater on the plateau than on the cliff face.

Table 5. Breeding success of the Northern Gannet at Bonaventure Island in 2009.

Sub-colony	Number of eggs[1]	Number of chicks[2]	Number of fledglings[3]	Hatching success[4]	Fledging success[5]	Net productivity[6]
A (plateau)	47	33	31	70.2%	93.9%	66.0%
B2 (plateau)	68	44	41	66.7%	93.2%	60.3%
C (cliff)	51	28	18	54.9%	69.2%	36.7%
D (plateau)	40	18	16	45.0%	88.9%	40.0%
E (plateau)	86	55	53	64.0%	98.1%	62.4%
F (plateau)	43	24	15	58.5%	62.5%	34.9%
G (plateau)	70	40	23	58.8%	85.2%	50.0%
H (cliff)	55	19	8	35.8%	42.1%	14.5%
Total plateau	354	214	179	61.5%	89.5%	57.4%
Total cliff	106	47	26	45.2%	57.8%	25.0%
Grand total	460	261	205	57.7%	83.7%	49.7%

[1]Number of nests where an egg was laid, in the sample
[2]Number of eggs hatched, among those of the preceding column
[3]Number of juveniles present on the last visit (4-5 September); alive and ready to fledge
[4]Number of chicks / number of eggs in the sample
[5]Number of juveniles ready to fledge / number of chicks
[6]Number of juveniles ready to fledge / number of eggs in the sample

Table 6 shows the trend in breeding success for the Bonaventure Island population beginning in the 1960s, when the first studies were conducted. As mentioned earlier, the lower hatching success observed until 1974 was linked to eggshell thinning caused by DDT (Chapdelaine et al. 1987). Afterwards, reproductive success remained fairly high for nearly 30 years, ranging from 68 to 77% between 1976 and 2005. The net productivity estimate for 2009 (50%) is the lowest level recorded since the period of high DDT levels in the environment.

Table 6. Trend in breeding success of the Northern Gannet at Bonaventure Island between 1966 and 2009

Year	Number of eggs (n)	Hatching success	Fledging success	Net productivity	Source[2]
1966	437	40 % [1]	78 % [1]	30 % [1]	1
1967	507				
1970	261	37 %	85 %	31 %	2
1974	503	58 %	77 %	45 %	3
1976	474	85 %	80 %	69 %	4
1979	489	89 %	87 %	77 %	4
1984	531	78 %	96 %	75 %	4
1989	456	83 %	87 %	72 %	5
1994	449	81 %	90 %	73 %	5
1999	431	86 %	86 %	74 %	5
2004	584	78 %	93 %	73 %	5
2005	543	75 %	91 %	68 %	5
2009	460	58 %	84 %	50 %	5

[1]data of 1966 and 1967 combined

[2] 1 = Poulin 1968; 2 = Y. Turgeon, unpublished data; 3 = P. S. Taylor and D.N. Nettleship, unpublished data; 4 = Chapdelaine et al. 1987; 5 = Canadian Wildlife Service (Quebec Region)

3.3 GANNET DIET ON BONAVENTURE ISLAND

Gannet diet was studied more intensively in 2004 and 2005, when sampling of regurgitations was conducted in four campaigns lasting 1 to 3 days each, separated by intervals of 12 to 20 days and spread over 2 months. The number of samples collected varied between 4 and 45 regurgitations per day, that is, between 23 and 68 regurgitations per campaign, for a total of 142 regurgitations in 2004 and 249 in 2005 (Figure 4).

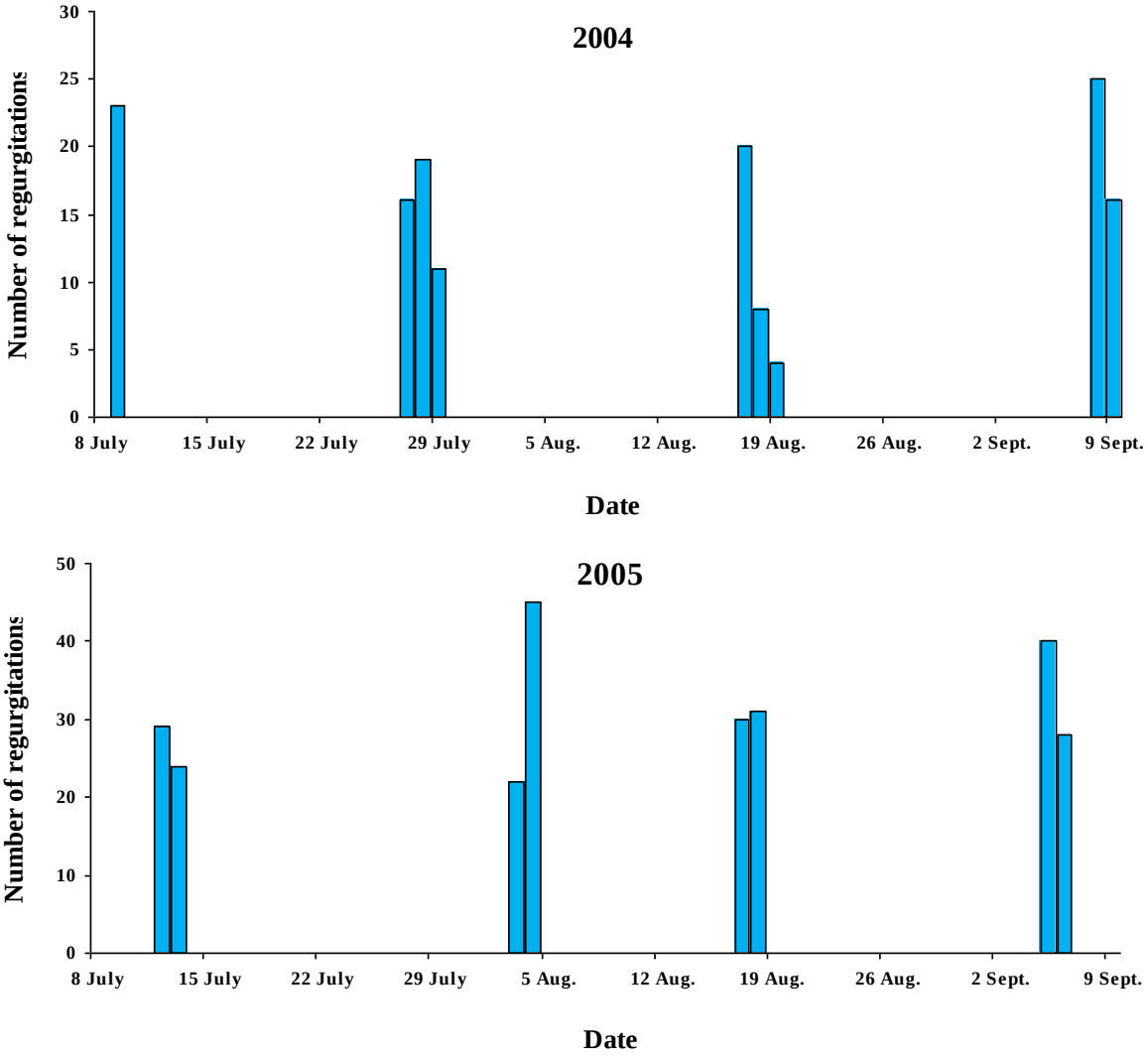

Figure 4. Sampling of Northern Gannet regurgitations at Bonaventure Island in 2004 and 2005.

The sampling conducted in 2004 and 2005 showed that during the chick-rearing period (from July to September), the diet of the gannets at the Bonaventure Island colony consisted primarily of Atlantic Mackerel (*Scomber scombrus*) and Atlantic Herring (*Clupea harengus*) (tables 7 and 8). Certain prey species such as Capelin (*Mallotus villosus*), Sand Lance (*Ammodytes sp*.) and Plaice (*Pleuronectidae spp.*) may also be a regular component of the gannet diet, but the amount of energy they contribute appears to be fairly low.

Table 7. Diet of the Northern Gannet at Bonaventure Island, summer 2004.

N=142	Frequency of occurence[1]		Numerical frequency[2]		Mass	
Taxon	**n**	**(%)**	**n**	**(%)**	**(g)**	**(%)**
Mackerel	78	(54.9)	106	(32.4)	11 841	(51.6)
Clupeidae*	63	(44.4)	99	(30.3)	10 282	(44.8)
Capelin	5	(3.5)	25	(7.6)	300	(1.3)
Sandlance**	9	(6.3)	94	(28.7)	443	(1.9)
Unid. flatfish	1	(0.7)	1	(0.3)	31	(0.1)
Unid. fish	2	(1.4)	2	(0.6)	46	(0.2)
Total			327	(100.0)	22943	(100.0)

[1]Number of regurgitations where the prey taxon was found
[2]Number of individuals of the prey taxon found in all the regurgitations
*Probably nearly always Atlantic herring, but other clupeidae species also possible
**Ammodytes sp.

Table 8. Diet of the Northern Gannet at Bonaventure Island, summer 2005.

N=249	Frequency of occurence		Numerical frequency		Mass	
Taxon	**n**	**(%)**	**n**	**(%)**	**(g)**	**(%)**
Mackerel	183	(73.5)	283	(50.3)	32 532	(69.8)
Clupeidae*	85	(34.1)	163	(29.0)	13 053	(28.0)
Capelin	1	(0.4)	1	(0.2)	13	(0.0)
Sandlance**	9	(3.6)	107	(19.0)	488	(1.0)
Unid. flatfish	1	(0.4)	1	(0.2)	57	(0.1)
Gunnel sp.	2	(0.8)	2	(0.4)	132	(0.3)
Cod sp.	2	(0.8)	2	(0.4)	275	(0.6)
Unid. squid	2	(0.8)	2	(0.4)	53	(0.1)
Stickleback sp.	1	(0.4)	1	(0.2)	1	(0.0)
Unid. fish	1	(0.4)	1	(0.2)	9	(0.0)
Total			563	(100.0)	46613	(100.0)

[1]Number of regurgitations where the prey taxon was found
[2]Number of individuals of the prey taxon found in all the regurgitations
*Probably nearly always Atlantic herring, but other clupeidae species also possible
**Ammodytes sp.

Table 9. Diet of the Northern Gannet at Bonaventure Island, summer 2009.

N=73	Frequency of occurence		Numerical frequency		Mass	
Taxon	**n**	**(%)**	**n**	**(%)**	**(g)**	**(%)**
Mackerel	36	(49.3)	52	(21.9)	6 101	(53.1)
Clupeidae*	20	(27.4)	26	(11.0)	2 817	(24.5)
Capelin	11	(15.1)	107	(45.1)	1 393	(12.1)
Sandlance**	3	(4.1)	24	(10.1)	52	(0.5)
Unid. Osmeridae***	2	(2.7)	3	(1.3)	13	(0.1)
Atlantic saury	6	(8.2)	21	(8.9)	1 056	(9.2)
Unid. fish	2	(2.7)	4	(1.7)	67	(0.6)
Total			237	(100.0)	11499	(100.0)

[1]Number of regurgitations where the prey taxon was found
[2]Number of individuals of the prey taxon found in all the regurgitations
*Probably nearly always Atlantic herring, but other clupeidae species also possible
**Ammodytes sp.
***Capelin or Rainbow smelt

In 2009, however, the analysis results for the regurgitations (*n*=73) that were collected opportunistically were somewhat surprising (Table 9). Although mackerel and herring were still the most important species in the gannet diet, appreciable quantities of two other species were found as well. Capelin accounted for more than 12% of the mass of prey measured, but the big surprise was the presence of Atlantic Saury (*Scomberesox saurus*), which was reported for the first time in diet studies on Bonaventure Island, and represented a significant proportion of the diet (9.2% of the mass of regurgitations).

The proportion of herring and mackerel in the diet at this colony may vary considerably between years, and even from day to day. For example, during the first 3 sampling campaigns in 2004, mackerel made up between 59 and 77% of the mass of the prey, whereas on the last visit the corresponding proportion fell to just 17%. On September 8 and 9, 2004, Atlantic Herring (80% by weight) appears to have replaced mackerel as the main component of the gannet diet (Figure 5).

The following year, during the third sampling campaign (on August 17 and 18, 2005), herring was particularly well represented in the diet, accounting for 66% of the mass of prey analyzed. Mackerel made up at least 74% of the regurgitations sampled during the other 3 visits (Figure 6).

In 2009, Capelin made up a sizeable proportion of the diet during the first sampling campaign, accounting for more than 40% of the regurgitation contents (by mass) on July 11 and 12, and more than half of the mass of regurgitated food on July 12 alone. On July 21 and 23, diet composition seemed more typical, consisting of two thirds mackerel and one third herring; however, the level of sampling was very low (6 regurgitations). Lastly, in early September, a considerable amount of Atlantic Saury was found in the regurgitations (15% by mass) (Figure 7).

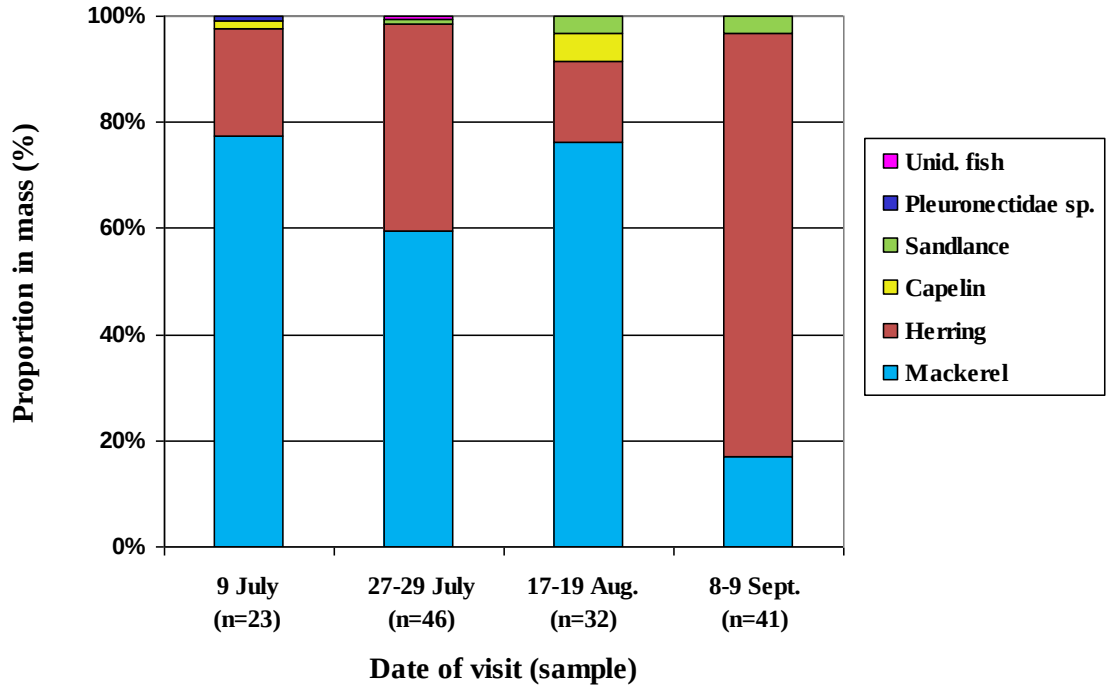

Figure 5. Seasonal variation of the diet of the Northern Gannet at Bonaventure Island, summer 2004.

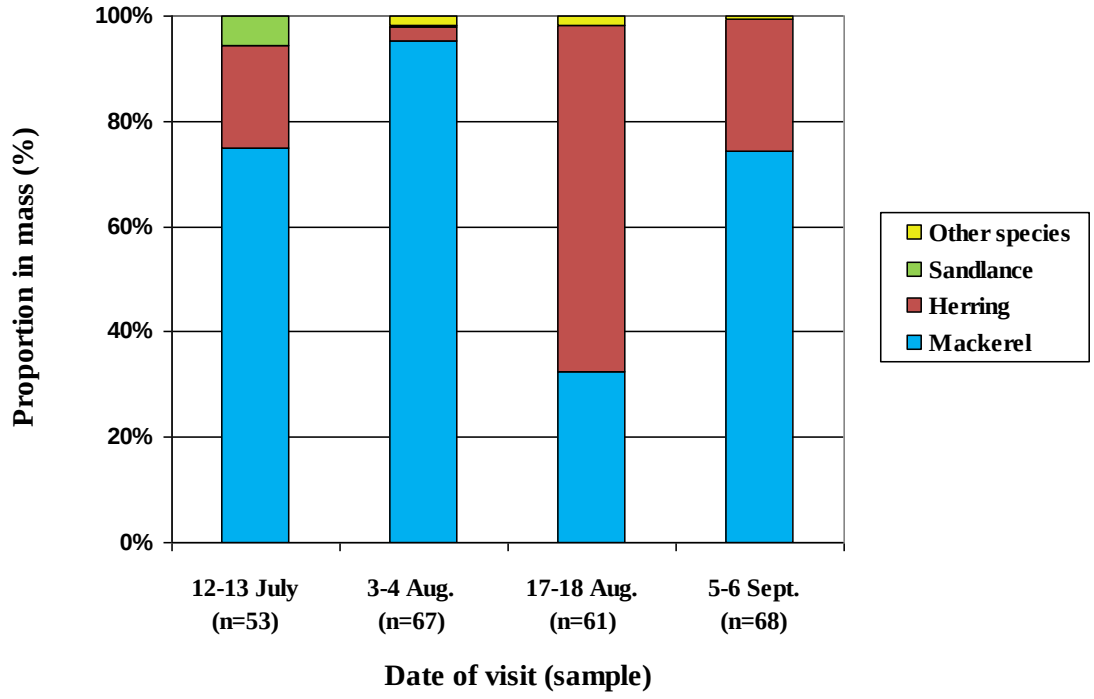

Figure 6. Seasonal variation of the diet of the Northern Gannet at Bonaventure Island, summer 2005.

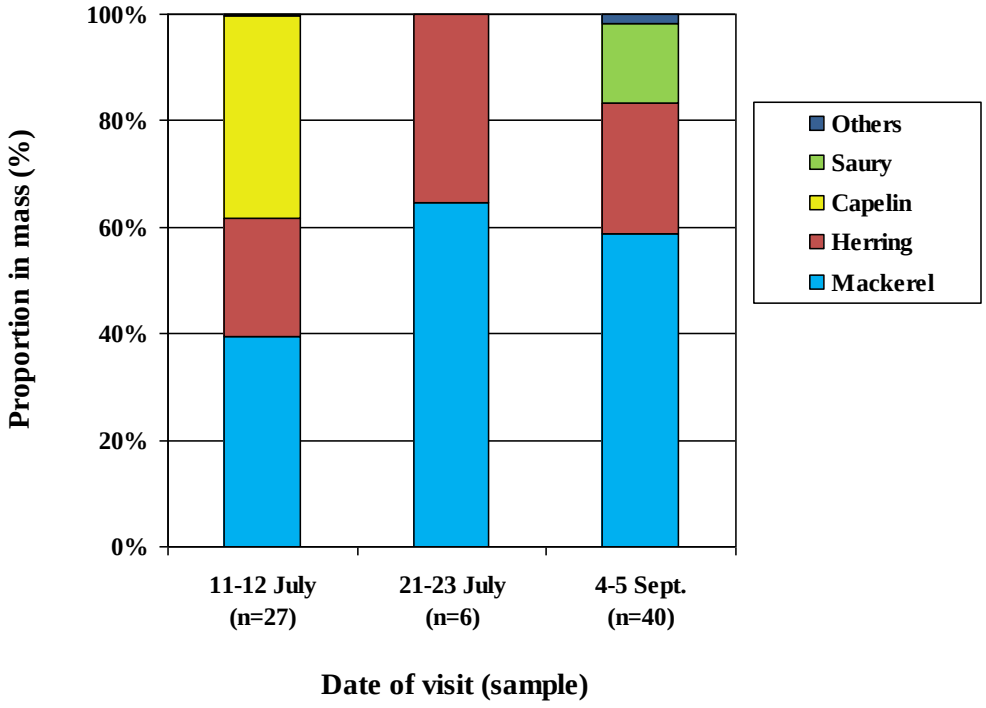

Figure 7. Seasonal variation of the diet of the Northern Gannet at Bonaventure Island, summer 2009.

3.4 CHEMICAL ANALYSES FOR BONAVENTURE ISLAND

3.4.1 Mercury and other inorganic elements

Based on the analysis of variance ($F_{8, 16} = 2.81$, $p > 0.05$), there were no significant differences among years in mercury levels. However, Tukey's test showed that mean mercury concentration was significantly lower in 2009 than in 1969 (Table 10). Mercury concentrations showed a slight but significant decrease of 12% during the period 1969 to 2009 (annual decrease of 0.3%) based on the slope of the linear regression (Figure 8; $y = 6.91 – 0.0033x$; $R^2 = 0.32$; $F_{1,15} = 6.97$, $p = 0.02$).

The concentrations of the inorganic elements measured in eggs in 2009 are shown in Table 11. Zinc (Zn) was found to have the highest concentration, followed by Cu, Se, Rb, Mn and As.

Table 10. Mean concentrations of mercury (mg/kg wet weight ± standard deviation, min-max) in Northern Gannet eggs from Bonaventure Island

Year	nb	Moisture (%)	Mercury (mg/kg wet weight)		
			Mean	Standard dev.	Minimum–maximum
1969	1 (5)	83.0	0.45 [a]		0.32–0.59
1973	1 (5)	82.9	0.33 [ab]		0.32–0.35
1976	1 (5)	85.1	0.27 [ab]		0.18–0.35
1984	1 (5)	83.4	0.33 [ab]		0.30–0.36
1989	1 (5)	82.4	0.27 [ab]		0.21–0.34
1994	3 (15)	82.6	0.33 [ab]	0.06	0.26–0.39
1999	3 (15)	83.8	0.28 [ab]	0.03	0.24–0.30
2004	3 (15)	83.5	0.32 [ab]	0.05	0.27–0.41
2009	3 (15)	83.3	0.20 [b]	0.02	0.18–0.22

Values followed by the same letter are not significantly different ($p > 0.05$). The number of pooled samples is given with the total number of eggs (n) in parenthesis

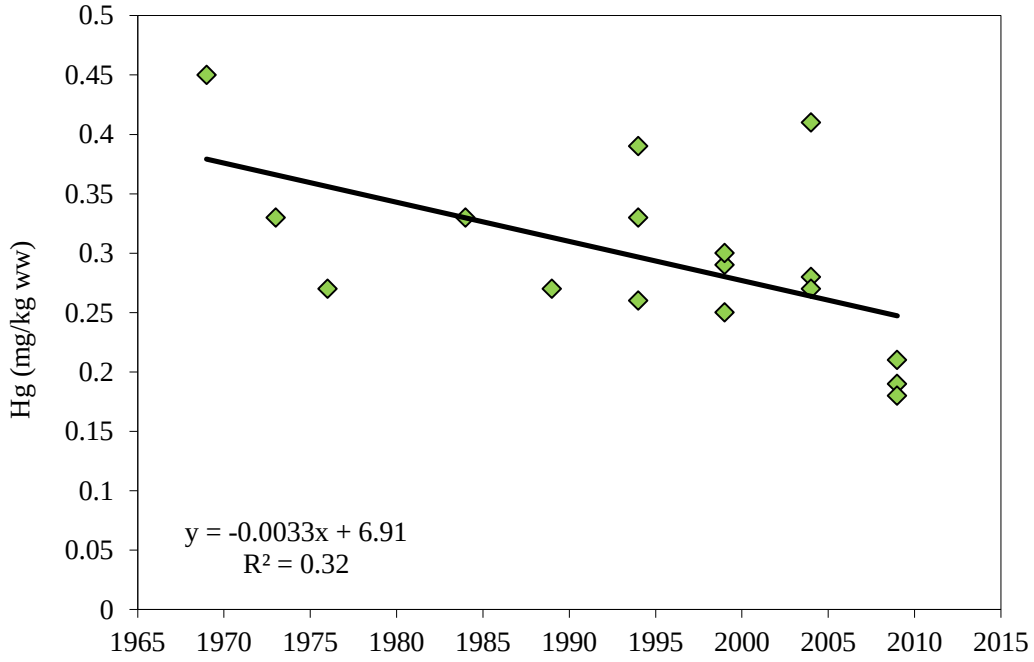

Figure 8. Temporal trends in concentrations of mercury in Northern Gannet eggs from Bonaventure Island, 1969 to 2009.

Table 11. Concentrations (mg/kg dw) in inorganic elements in Northern Gannet eggs collected in Bonaventure Island in 2009

	Moisture (%)	As	Cd	Cu	Mn	Pb	Rb	Se	Zn
Detection limit		0.063	0.001	0.075	0.01	0.063	0.063	0.125	1.375
Mean	83.2	0.482	<0.001	3.36	1.17	<0.06	1.75	3.21	37.0
Standard deviation	0.04	0.053		0.08	0.27		0.10	0.24	1.7

3.4.2 Polychlorinated biphenyls, organochlorine pesticides, dioxins-furans and brominated flame retardants

The concentrations of ΣPCB_{38}, PCB 1:1, the penta-PCB, hexa-PCB and hepta-PCB homologue groups, and the 2-ortho and 4-ortho groups (congeners with 2 or 4 ortho-substituted chlorine atoms) show significant differences between years ($p < 0.001$). The concentrations of ΣPCB_{38}, PCB 1:1 and the 1-ortho, 2-ortho, 4-ortho and tetra-, penta-, hexa-, hepta- and octa-PCB groups show a decrease over time ($p < 0.001$; Table 12; figures 9 and 10). The other groups do not show significant between-year differences or a temporal trend ($p > 0.05$). Based on the mean annual concentrations, PCB 1:1 decreased by 92.3% from 1969 to 2009 and ΣPCB_{38} by 60.9% from 1989 to 2009.

The 6 main PCB congeners present in gannet eggs, accounting for 61% of ΣPCB_{38} on average, were as follows: congener 153 > 138 > 187 > 180 > 118 > 206. Among these congeners, PCB 118, 138, 153 and 180 showed significant between-year differences and significant temporal trends ($p < 0.001$; Figure 11; Table 12). The 2-ortho and 3-ortho groups made up about 89% of ΣPCB_{38}, followed by the 1-ortho and finally the 4-ortho groups, throughout the entire study (Figure 12). Similarly, moderately chlorinated congeners (penta-, hexa- and hepta-PCB) were present at higher levels, with a mean contribution of 85%, than strongly (octa- and nona-PCB) or weakly (tri- and tetra-PCB) chlorinated congeners (Figure 12). The half-lives of the PCB congeners and groups ranged from 8.6 years for tetra-PCB to 23.9 years for 3-ortho-PCBs. The half-lives of PCB 1:1 and ΣPCB_{38} were, respectively, 10.5 and 13.9 years (Appendix 8).

Most of the 21 organochlorine pesticides (OCs) measured in eggs (16 compounds), specifically α-HCH, *p,p*'-DDT, *p,p*'-DDD, *p,p*'-DDE, *trans*-nonachlor, *cis*-nonachlor, oxychlordane, *trans*-chlordane, *cis*-chlordane, heptachlor epoxide, dieldrin, mirex, pentaCB, HCB, OCS and TCPM exhibited significant between-year differences. Significant temporal declines were observed for 11 of these compounds (α-HCH, *p,p*'-DDT, *p,p*'-DDD, *p,p*'-DDE, *trans*-nonachlor, *cis*-nonachlor, oxychlordane, *cis*-chlordane, heptachlor epoxide, dieldrin and mirex) (Figure 13; Table 13). None of the OCs showed an increase in concentration over time. The 6 predominant organochlorine pesticides were as follows (in descending order): *p,p*'-DDE, *trans*-nonachlor, dieldrin and *cis*-nonachlor, oxychlordane and *cis*-chlordane (Figure 13). On average, they made up 97% of the total OC concentrations observed during the study. The concentration of *p,p*'-DDE, the primary metabolite of DDT, decreased sharply between 1969 and 1976 and more slowly thereafter. Figure 14 illustrates the temporal trend in the *p,p*'-DDE concentration in eggs in relation to hatching success, net productivity and total population size. The sums of the isomers of the organochlorine pesticides all decreased significantly over time, with the largest decrease occurring in the sum of the DDT isomers (ΣDDT: slope = -0.053; $p < 0.001$) and the smallest in the sum of the chlordanes (ΣCHLOR: slope = -0.025; $p < 0.001$; Table 13). The sum of the organochlorine pesticides (ΣOC) also decreased significantly over time (slope = -0.045; $p < 0.001$). The half-lives of the organochlorine pesticides ranged from 3.5 years for *p,p*'-DDD to 21.0 years for α-HCH (Appendix 8).

BFRs were measured in 2004 and 2009 (Table 14). The main congeners analyzed in 2004, BDE-47, BDE-49 and BDE-100, accounted for 57% of the total PBDE concentrations (and 51% of total BFRs), with BDE-47 being the dominant congener. In 2009, these congeners represented 59% of the total PBDE concentrations (and 59% of total BFRs), and BDE-49 was the dominant congener. Only 8 congeners measured in 2004 were also detected in 2009, including BDE-47, BDE-49, BDE-99, BDE-100 and BDE-153. They accounted for 80 and 88% of the BDEs (72 and 88% of total BFRs) in 2004 and 2009,

respectively. Six other congeners were analyzed in 2009 (2 of which were above the detection limit), but they were excluded from the statistical analyses because they were not analyzed in 2004. The most highly brominated BDEs (hexa- and hepta-) accounted for a greater proportion of the total BFRs in 2004, whereas the least brominated ones (tetra- and penta-) made a greater relative contribution in 2009, which points to a transition (or degradation) toward less brominated congeners. The sum of the tetra-, penta- and hexabromodiphenyl ether compounds made up 98.0 and 98.6% of the total BFRs in 2004 and 2009, respectively. The concentrations of only one congener, BDE-138, differed significantly between 2004 and 2009 ($p < 0.05$; Table 14). However, the proportions of some congeners differed between the two years (Figure 15).

The dioxin, furan and non-ortho-PCBs concentrations measured in eggs in 2004 and 2009 are presented in Table 15. A toxic equivalent (TEQ) was calculated for mono-ortho-substituted congeners (105, 118, 156 and 157), non-ortho-PCBs (77, 81, 126 and 169) and dioxins and furans (see Section 2.6). On average, non-ortho-PCBs contributed 71.5% and 77.0% of the total TEQ in 2004 and 2009, respectively. The total concentrations of the different groups were compared between the two years. Significant differences were found in the total dioxins and furans, as well as in the TEQ of the dioxins ($p < 0.05$).

Table 12. Mean concentrations (mg/kg ww ± standard deviation) and trends in polychlorinated biphenyls in Northern Gannet eggs from Bonaventure Island

Year	**1969**	**1973**	**1974**	**1976**	**1984**	**1989**	**1994**		**1999**		**2004**		**2009**		**Trend[A]**	**Slope**	***R²***
***n* (nb eggs)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**3 (15)**		**3 (15)**		**3 (15)**		**3 (15)**				
% lipids	4.8	3.6	3.9	4.4	3.9	4.1	4.6	± 0.5	5.0	± 0.1	5.3	± 0.3	4.4	± 0.4			
PCB -118						0.259^{a}	0.180	± 0.011^{ab}	0.139	± 0.033^{b}	0.074	± 0.012^{c}	0.077	± 0.003^{c}	↓	-0.008	0.85
PCB -138						0.450^{a}	0.337	± 0.019^{b}	0.253	± 0.033^{c}	0.152	± 0.023^{d}	0.162	± 0.006^{d}	↓	-0.014	0.86
PCB -153						0.693^{a}	0.458	± 0.027^{b}	0.430	± 0.059^{b}	0.272	± 0.038^{c}	0.298	± 0.011^{c}	↓	-0.017	0.75
PCB -180						0.232^{a}	0.205	± 0.020^{a}	0.147	± 0.016^{b}	0.094	± 0.013^{c}	0.119	± 0.006^{bc}	↓	-0.006	0.73
PCB -187						0.183^{a}	0.181	± 0.023^{a}	0.142	± 0.018^{a}	0.095	± 0.013^{b}	0.165	± 0.005^{a}	ns		
PCB -206						0.067	0.090	± 0.018	0.085	± 0.030	0.077	± 0.015	0.087	± 0.011	ns		
1-ortho						0.466	0.334	± 0.015	0.291	± 0.158	0.126	± 0.022	0.125	± 0.006	↓	-0.032	0.76
2-ortho						2.314^{a}	1.507	± 0.101^{ab}	1.199	± 0.210^{b}	0.730	± 0.108^{c}	0.813	± 0.029^{c}	↓	-0.023	0.79
3-ortho						0.618	0.518	± 0.072	0.397	± 0.075	0.285	± 0.039	0.393	± 0.021	ns		
4-ortho						0.081^{a}	0.075	± 0.010^{a}	0.079	± 0.021^{a}	0.058	± 0.012^{a}	0.009	± 0.001^{b}	↓	-0.048	0.63
Tri- PCB						0.095	0.012	± 0.002	0.050	± 0.076	0.005	± 0.001	0.005	± 0.000	ns		
Tetra- PCB						0.078	0.097	± 0.007	0.086	± 0.076	0.031	± 0.008	0.018	± 0.002	↓	-0.042	0.69
Penta- PCB						0.527^{a}	0.356	± 0.021^{a}	0.268	± 0.088^{a}	0.138	± 0.027^{b}	0.149	± 0.006^{b}	↓	-0.029	0.80
Hexa- PCB						1.605^{a}	1.038	± 0.060^{b}	0.838	± 0.113^{b}	0.521	± 0.076^{c}	0.570	± 0.022^{c}	↓	-0.022	0.81
Hepta- PCB						0.922^{a}	0.626	± 0.065^{a}	0.458	± 0.055^{b}	0.293	± 0.040^{c}	0.408	± 0.016^{b}	↓	-0.018	0.60
Octa- PCB						0.186	0.216	± 0.030	0.181	± 0.041	0.133	± 0.022	0.103	± 0.009	↓	-0.018	0.73
Nona- PCB						0.067	0.090	± 0.018	0.085	± 0.030	0.077	± 0.015	0.087	± 0.011	ns		
Total PCB						3.874	2.673	± 0.220	2.384	± 0.587	1.473	± 0.192	1.494	± 0.032	na		
$\sum PCB_{38}$						3.480^{a}	2.435	± 0.192^{ab}	1.966	± 0.455^{bc}	1.198	± 0.160^{d}	1.340	± 0.042^{cd}	↓	-0.021	0.77
PCB 1:1	28.8^{a}	20.4^{a}	18.0^{ab}	16.2^{ab}	10.1^{bc}	6.14^{cd}	4.59	± 0.25^{de}	3.47	± 0.45^{e}	2.09	± 0.31^{f}	2.22	± 0.09^{f}	↓	-0.029	0.97

[A] Decreasing (↓) or non-significant (ns, $p > 0.001$) temporal trends for log-transformed (base 10) concentrations of contaminants determined by simple linear regression analysis. The number of composite samples (n) is given with the number of eggs in parenthesis. Values on the same line followed by the same letter are not significantly different (ANOVA, $p > 0.001$). The signification level α has been corrected with the Bonferroni method for the number of tests done (41 contaminants ; $\alpha = 0.05 / 41 = 0.001$)

Table 13. Mean concentrations (mg/kg ww ± standard deviation) and trends in organochlorinated pesticides in Northern Gannet eggs from Bonaventure Island

Year	1969	1973	1974	1976	1984	1989	1994	1999	2004	2009	Trend[A]	Slope	R^2
n **(nb eggs)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**1(5)**	**3 (15)**	**3 (15)**	**3 (15)**	**3 (15)**			
α-HCH	0.006 [b]	0.008 [ab]	0.008 [a]	0.009 [a]	0.008 [a]	0.002[de]	na	0.004±0.000 [c]	0.004±0.001 [cd]	0.002±0.000 [e]	↓	-0.0002	0.74
β-HCH	0.007[abc]	0.014[a]	0.010[ab]	0.009[abc]	0.002[bcd]	0.004[abc]	na	0.001±0.000 [d]	0.004±0.001 [abc]	0.002±0.000 [cd]	ns		
γ-HCH	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	ns		
Total HCH	0.013[ab]	0.021[a]	0.019[a]	0.019[ab]	0.010[bc]	0.006[cd]	<0.001	0.005±0.000 [d]	0.007±0.001 [c]	0.004±0.000 [d]	ns		
pp'-DDT	1.297[a]	0.919[a]	0.694[ab]	0.550[abc]	0.151[bc]	0.121[c]	na	0.001±0.000 [f]	0.013±0.002 [d]	0.004±0.001 [e]	↓	-0.071	0.73
pp'-DDD	2.958[a]	0.565 [ab]	0.609[ab]	0.454[b]	0.134[bc]	0.040[c]	na	0.002±0.001 [d]	0.002±0.001 [d]	0.001±0.000 [d]	↓	-0.086	0.97
pp'-DDE	17.09[a]	9.432 [ab]	7.108[b]	3.269[c]	1.108[d]	0.725[d]	0.388±0.028 [e]	0.259±0.021 [f]	0.172±0.026 [g]	0.106±0.008 [h]	↓	-0.052	0.97
Total DDT	19.10[a]	10.16 [b]	7.738[b]	3.730[c]	1.241[d]	0.886[d]	0.389±0.028 [e]	0.262±0.021 [f]	0.187±0.028 [f]	0.111±0.008 [g]	↓	-0.053	0.97
t-nonachlor						0.178[a]	0.106±0.015 [b]	0.062±0.008 [c]	0.056±0.005 [cd]	0.032±0.004 [d]	↓	-0.006	0.84
c-nonachlor	0.188[a]	0.182 [a]	0.196[a]	0.201[a]	0.114[ab]	0.069[b]	na	0.023±0.002 [c]	0.017±0.002 [cd]	0.012±0.001 [d]	↓	-0.034	0.98
Oxychlordane	0.089[ab]	0.077 [b]	0.078[b]	0.104[a]	na	0.054[c]	na	0.017±0.003 [d]	0.045±0.005 [c]	0.010±0.001 [d]	↓	-0.002	0.79
c-chlordane	0.100[a]	0.081 [ab]	0.090[ab]	0.092[ab]	0.039[b]	0.015[c]	na	0.008±0.001 [cd]	0.007±0.001 [d]	0.004±0.000 [e]	↓	-0.037	0.97
t-chlordane		0.020 [ab]	0.022[ab]	0.017[b]	0.039[a]	0.001[c]	<0.001 [f]	<0.001 [e]	0.000±0.000 [d]	0.000±0.000 [d]	ns		
HE	0.041[a]	0.017 [bc]	0.025[abc]	0.030[ab]	0.028[abc]	0.018[bc]	0.017±0.003 [c]	0.009±0.001 [d]	0.008±0.001 [d]	0.005±0.000 [e]	↓	-0.020	0.84
Total chlordane	0.600[a]	0.525 [ab]	0.577 [ab]	0.610 [a]	0.308[b]	0.334[ab]	0.123±0.018 [c]	0.120±0.009 [c]	0.133±0.012 [c]	0.064±0.006 [d]	↓	-0.025	0.90
Dieldrin	0.580[a]	0.304 [ab]	0.256[bc]	0.295[ab]	0.142[cd]	0.088[de]	0.058±0.011 [ef]	0.048±0.004 [fg]	0.033±0.003 [gh]	0.026±0.002 [h]	↓	-0.032	0.97
photo-mirex						0.004	0.002±0.003	0.003±0.001	0.001±0.001	0.002±0.000	ns		
Mirex	0.023[a]	0.008 [bcd]	0.014[abc]	0.018[ab]	0.011[abc]	0.007[cde]	0.008±0.000 [c]	0.004±0.001 [de]	0.004±0.000 [e]	0.002±0.000 [f]	↓	-0.022	0.84
PentaCB						<0.001[a]	<0.001 [c]	<0.001 [a]	<0.001±0.000 [b]	<0.001±0.000 [ab]	ns		
HCB				0.019	0.013	0.007	0.005±0.001	0.007±0.001	0.007±0.004	0.010±0.001	ns		
OCS						0.003[a]	0.003±0.000 [a]	<0.001 [b]	<0.001 [c]	<0.001±0.000 [b]	ns		
TCPM						<0.001[d]	0.007±0.001 [ab]	0.004±0.001 [c]	0.005±0.001 [bc]	0.008±0.001 [a]	ns		
Total OC	19.18[a]	10.39 [b]	8.105[b]	4.427[c]	1.642[d]	1.336[d]	0.594±0.004 [e]	0.454±0.035 [f]	0.377 ±0.037 [f]	0.228 ±0.018 [g]	↓	-0.045	0.96

[A] Decreasing (↓) or non-significant (ns, p > 0.001) temporal trends for log-transformed (base 10) concentrations of contaminants determined by simple linear regression analysis. The number of composite samples (n) is given with the number of eggs in parenthesis. Values on the same line followed by the same letter are not significantly different (ANOVA, p > 0.001). The signification level α has been corrected with the Bonferroni method for the number of tests done (41 contaminants ; α = 0.05 / 41 = 0.001).

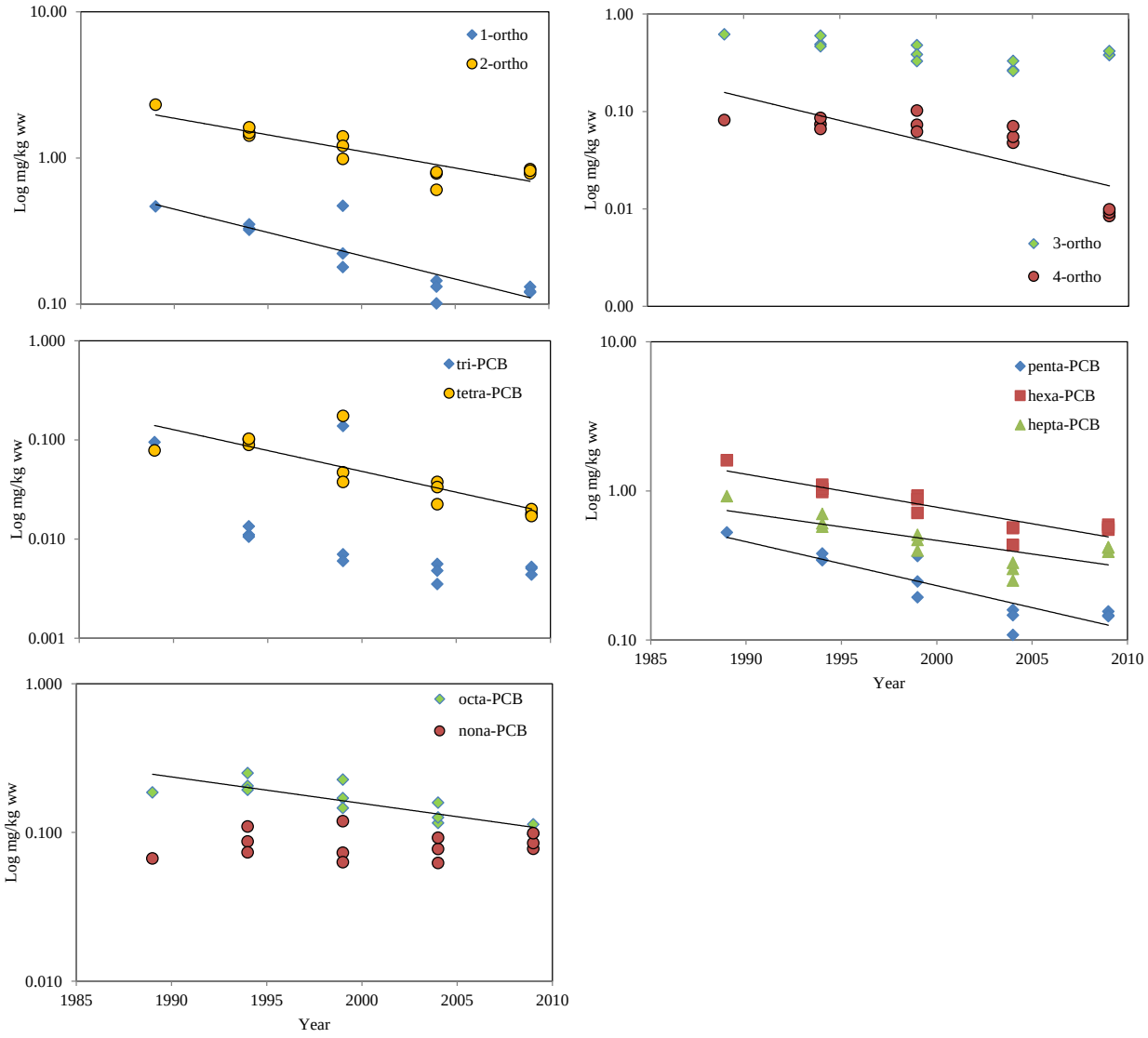

Figure 9. Temporal trends in concentrations of the ortho groups (from 1 to 4) and homolog groups (from tri- to nona-) of PCBs in Northern Gannet eggs from Bonaventure Island, 1989 to 2009.

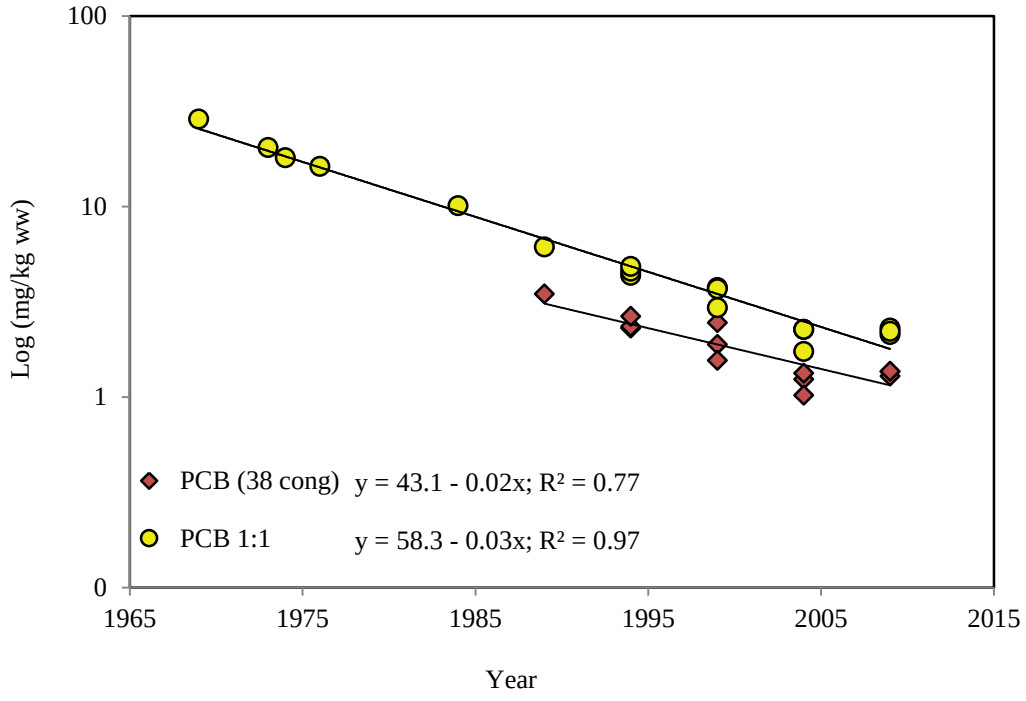

Figure 10. Temporal trends of ΣPCB_{38} (sum of 38 PCB congeners) and PCB 1:1 in Northern Gannet eggs from Bonaventure Island, 1969 to 2009.

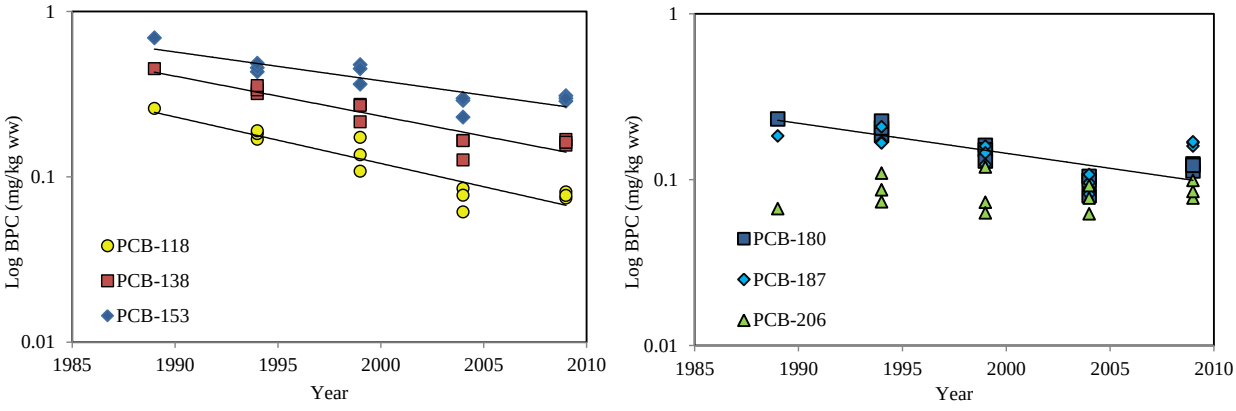

Figure 11. Temporal trends in concentrations of the main PCB congeners in Northern Gannet eggs from Bonaventure Island, 1989 to 2009

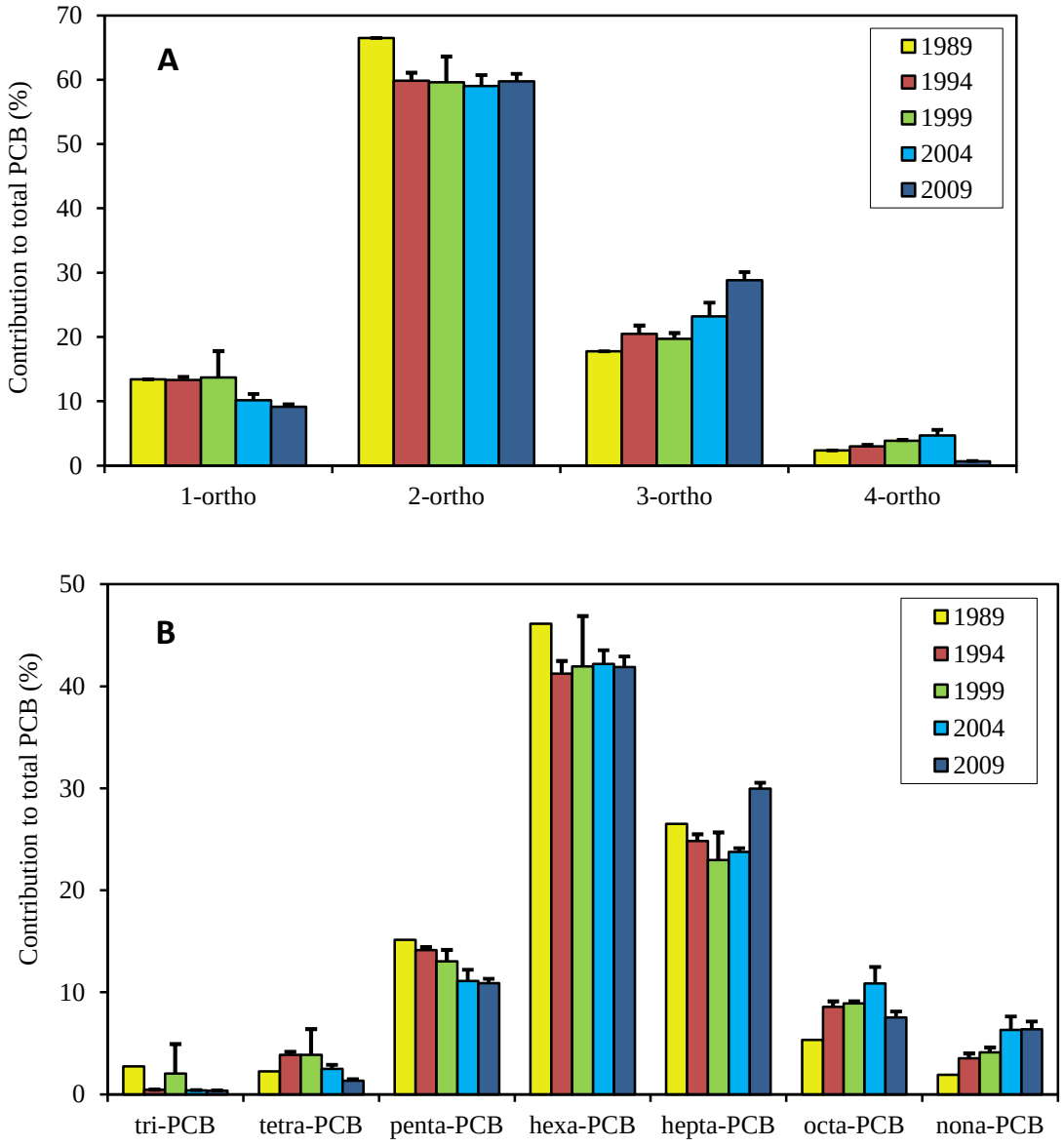

Figure 12. Contribution (% ± standard deviation) of A) ortho groups (from 1 to 4) and B) homolog groups (from tri- to nona-) to total PCBs (ΣPCB_{38}) in Northern Gannet eggs from Bonaventure Island, 1989 to 2009.

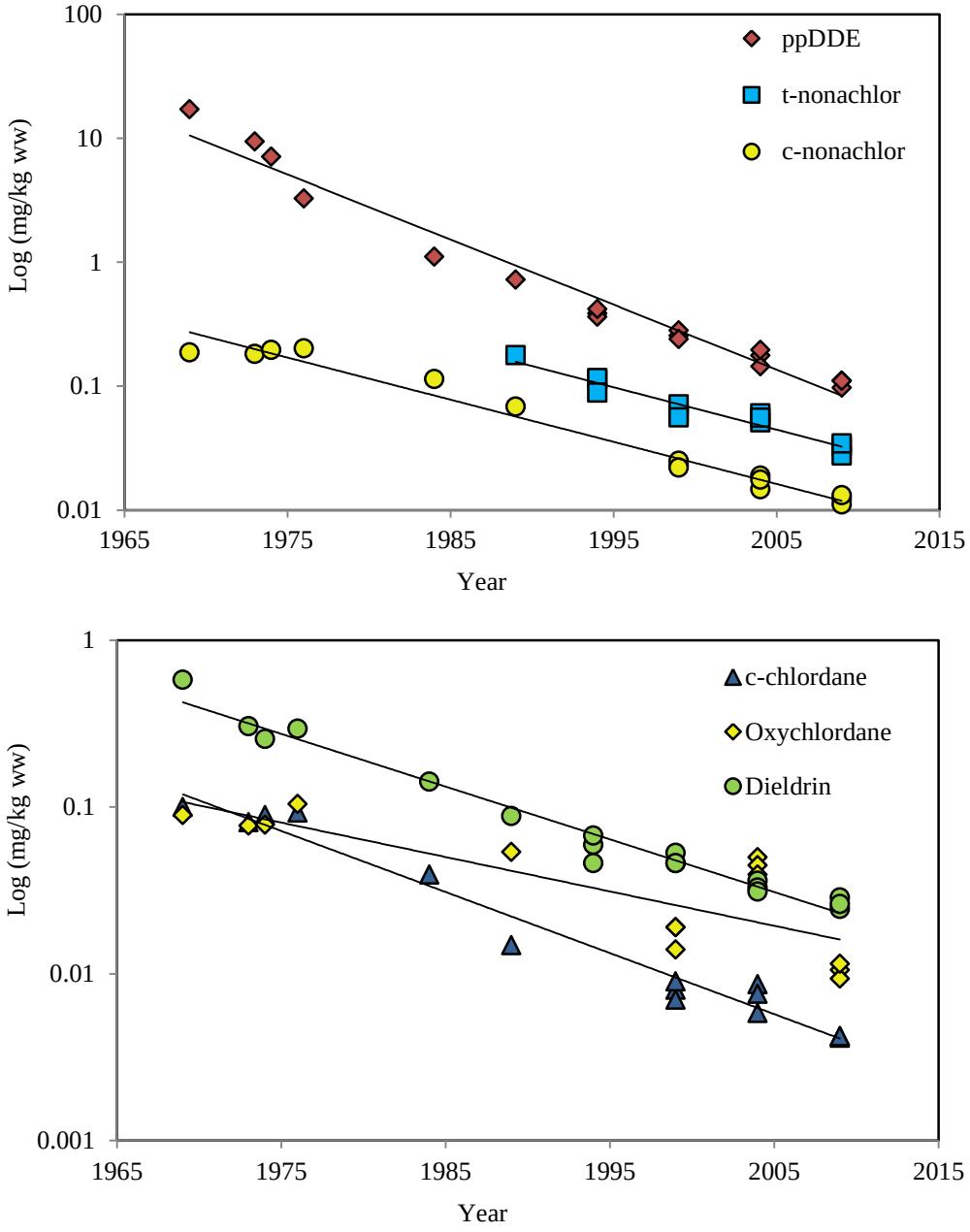

Figure 13. Temporal trends in concentrations of the main organochlorinated pesticides in Northern Gannet eggs from Bonaventure Island, 1969 to 2009.

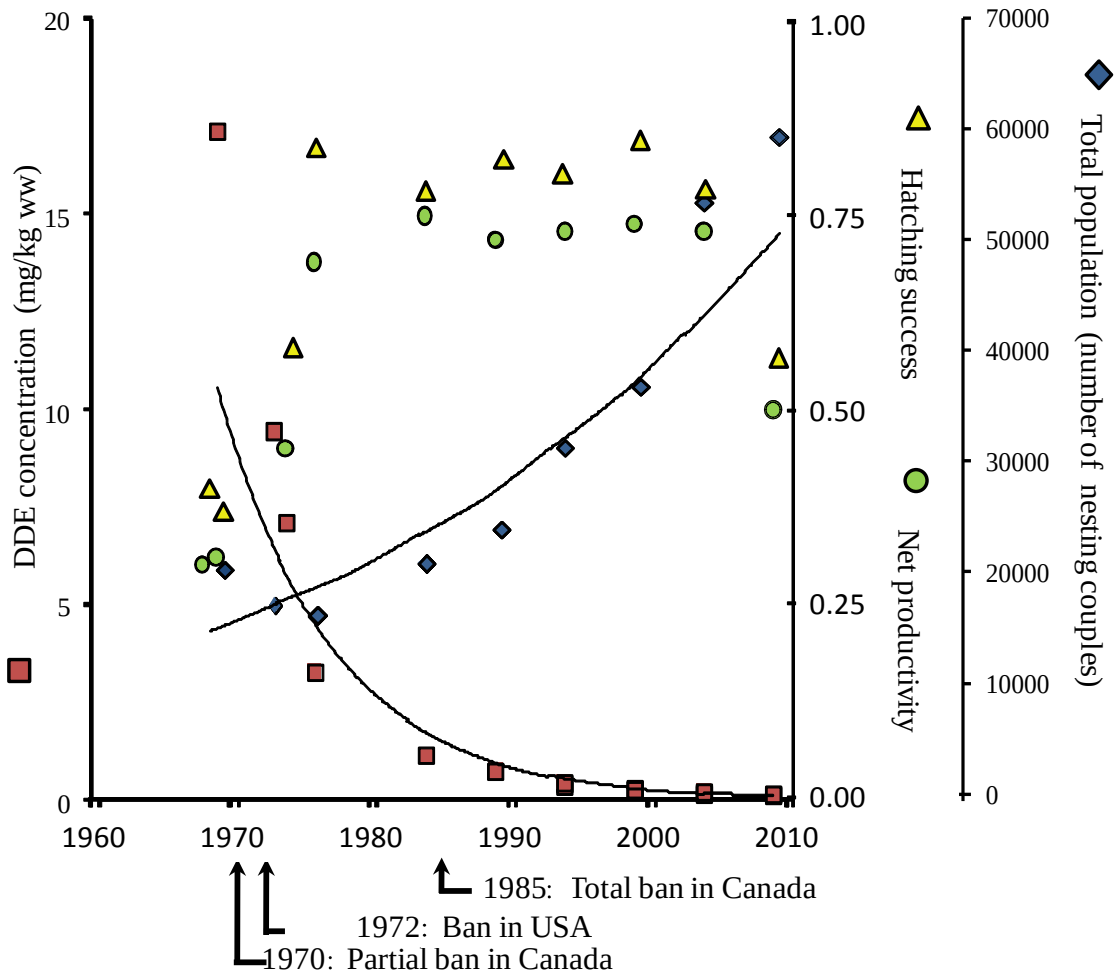

Figure 14. Temporal trend in the concentration of p,p'-DDE in eggs in relation with hatching success, net productivity and total population (number of nesting couples) of Northern Gannets from Bonaventure Island. The dates of DDT ban are indicated by arrows (U.S. EPA 1972; Environment Canada 2005).

Table 14. Mean concentrations (µg/kg ww ± standard deviation) of the main brominated flame retardants in Northern Gannet eggs from Bonaventure Island in 2004 and 2009

Year	**2004**		**2009**		
***n* (nb eggs)**	**3 (15)**		**3 (15)**		
% lipids	**5.25 ±**	**0.28**	**4.42 ±**	**0.37**	
BDE-15/B-TBECH	na		0.1 ±	0.0	
BDE-17	<0.1 ±	0.0	<0.1 ±	0.0	
BDE-28	0.15 ±	0.1	<0.1 ±	0.0	
BDE-47	9.3 ±	7.1	2.8 ±	0.5	
BDE-49	5.3 ±	2.3	4.9 ±	0.6	
BDE-66	<0.1 ±	0.0	<0.1 ±	0.0	
BDE-85	0.5 ±	0.7	<0.1 ±	0.0	
BDE-99	3.7 ±	2.6	2.5 ±	0.3	
BDE-100	5.4 ±	2.8	2.3 ±	0.2	
BB-101	0.8 ±	1.0	<0.1 ±	0.0	
BDE-138	1.9 ±	0.4	<0.1 ±	0.0	*
BDE-153	4.2 ±	2.4	2.5 ±	0.3	
BDE-154/BB-153	3.6 ±	2.1	1.6 ±	0.2	
HBCDD	3.6 ±	2.9	<0.1 ±	0.0	
BDE-183	0.22 ±	0.3	<0.1 ±	0.0	
BDE-190	0.4 ±	0.6	<0.1 ±	0.0	
BDE-209	<0.1 ±	0.0	<0.1 ±	0.0	
a-TBECH	na		<0.1 ±	0.0	
HBB	na		<0.1 ±	0.0	
BTBDE	na		<0.1 ±	0.0	
Syn-DP	na		0.2 ±	0.0	
Anti-DP	na		<0.1 ±	0.0	
Tri-BDE	0.2 ±	0.1	<0.1 ±	0.0	
Tetra-BDE	14.6 ±	9.3	7.7 ±	1.0	
Penta-BDE	10.4 ±	7.0	4.9 ±	0.5	
Hexa-BDE	13.4 ±	7.7	4.1 ±	0.5	
Hepta-BDE	0.6 ±	0.9	0.1 ±	0.0	
Deca-BDE	<0.1 ±	0.0	<0.1 ±	0.0	
Total PBDE	34.8 ±	21.1	16.9 ±	1.2	
Total BFR	39.2 ±	24.9	17.0 ±	1.2	

* Values significantly différent between years ($p < 0.05$)
na = not analysed.

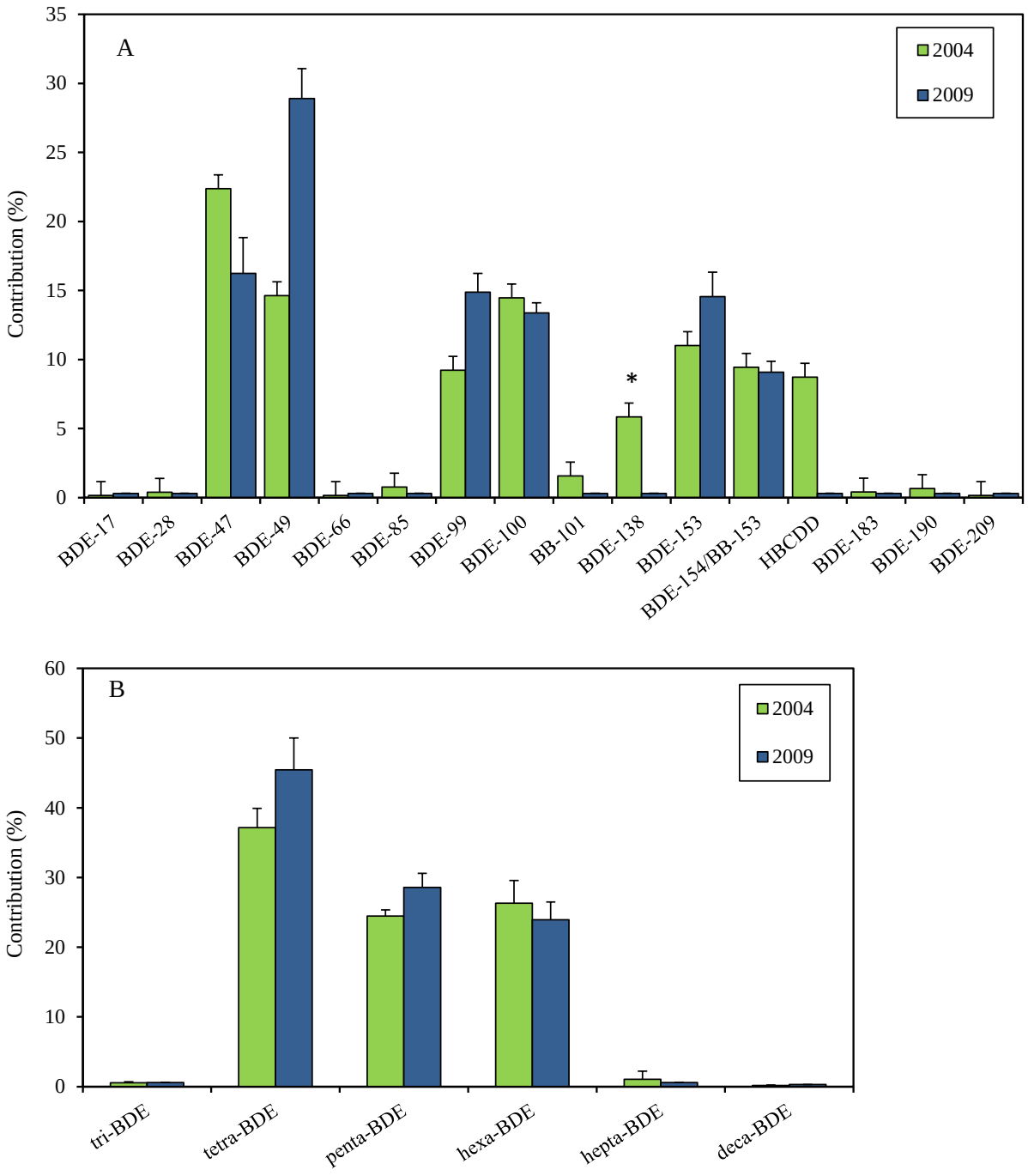

Figure 15. Contribution (% ± standard deviation) of A) BFR congeners and B) homolog groups to total BFRs in Northern Gannet eggs from Bonaventure Island in 2004 and 2009.

Table 15. Mean concentrations (ng/kg ww ± standard deviation) of dioxins, furans, non-ortho PCBs and toxic equivalent in Northern Gannet eggs from Bonaventure Island in 2004 and 2009

Year	**2004**			**2009**			
***n* (nb eggs)**	**3 (15)**			**3 (15)**			
2,3,7,8-TCDD	3.6	±	0.4	3.4	±	0.2	
1,2,3,7,8-PeCDD	7.7	±	0.8	6.6	±	0.5	
1,2,3,4,7,8-HxCDD	1.4	±	0.0	1.1	±	0.4	
1,2,3,6,7,8-HxCDD	5.3	±	0.4	3.7	±	0.5	
1,2,3,7,8,9-HxCDD	1.5	±	0.1	0.8	±	0.5	
1,2,3,4,6,7,8-HpCDD	1.8	±	0.3	1.0	±	0.6	
OCDD	5.5	±	1.8	4.9	±	1.1	
Total dioxins	26.7	±	2.7	21.4	±	2.1	
2,3,7,8-TCDF	31.1	±	2.6	29.4	±	4.7	
1,2,3,7,8-PeCDF	3.1	±	0.5	2.2	±	0.5	
2,3,4,7,8-PeCDF	7.1	±	1.4	5.5	±	0.7	
1,2,3,4,7,8-HxCDF	0.6	±	0.5	0.7	±	0.3	
1,2,3,6,7,8-HxCDF	0.5	±	0.1	0.4	±	0.1	
2,3,4,6,7,8-HxCDF	0.7	±	0.5	0.4	±	0.1	
1,2,3,7,8,9-HxCDF	0.3	±	0.1	0.2	±	0.1	
1,2,3,4,6,7,8-HpCDF	0.3	±	0.2	0.5	±	0.3	
1,2,3,4,7,8,9-HpCDF	0.3	±	0.1	0.3	±	0.1	
OCDF	0.8	±	0.4	1.2	±	0.3	
Total furans	44.6	±	4.2	40.7	±	4.6	
Total dioxins-furans	71.4	±	1.6	62.1	±	2.7	*
PCB-81	82.8	±	13.4	90.0	±	10.4	
PCB-77	1 713.3	±	213.9	2346.7	±	263.1	
PCB-126	458.3	±	75.1	430.0	±	47.6	
PCB-169	85.3	±	6.0	102.4	±	9.0	
Total non-ortho PCBs	2 339.7	±	308.0	2969.0	±	324.3	
Toxic equivalent[1]							
Total dioxins	11.6	±	0.5	10.1	±	0.6	*
Total furans	38.7	±	3.9	35.3	±	5.2	
Total non-ortho PCBs	139.9	±	19.5	169.4	±	18.7	
Total mono-ortho-PCBs	5.2	±	0.7	5.2	±	0.3	
Total toxic equivalent	195.3	±	22.7	220.0	±	23.4	

* Values significantly différent between years ($p < 0.05$)

[1] Concentrations multiplied by toxic equivalent factors (see section 2.6)

3.4.3 Eggshell thickness

Eggshell thickness varied significantly between the years ($F_{1,156}$ = 16.6, p < 0.001; Table 16, Figure 16). No contaminant showed a significant relationship with eggshell thickness (Table 18).

Table 16. Temporal evolution of eggshell thickness of Northern Gannet eggs from Bonaventure Island

Year	*n*	Mean (mm)	Standard deviation (mm)	Minimum–maximum (mm)
Pre-1947	8	0.59^{abc}	0.03	0.54-0.63
1968	9	0.50^{defg}	0.04	0.44-0.57
1969	21	0.48^{g}	0.04	0.42-0.57
1970	13	0.48^{fg}	0.05	0.40-0.54
1973	10	0.54^{cdef}	0.05	0.47-0.66
1974	30	0.52^{efg}	0.05	0.42-0.60
1976	6	0.54^{bcdefg}	0.02	0.52-0.58
1984	12	0.61^{ab}	0.05	0.54-0.66
1994	14	0.64^{a}	0.05	0.57-0.72
1999	15	0.55^{cde}	0.05	0.45-0.61
2004	15	0.55^{cde}	0.04	0.43-0.58
2009	15	0.57^{bcd}	0.04	0.49-0.66

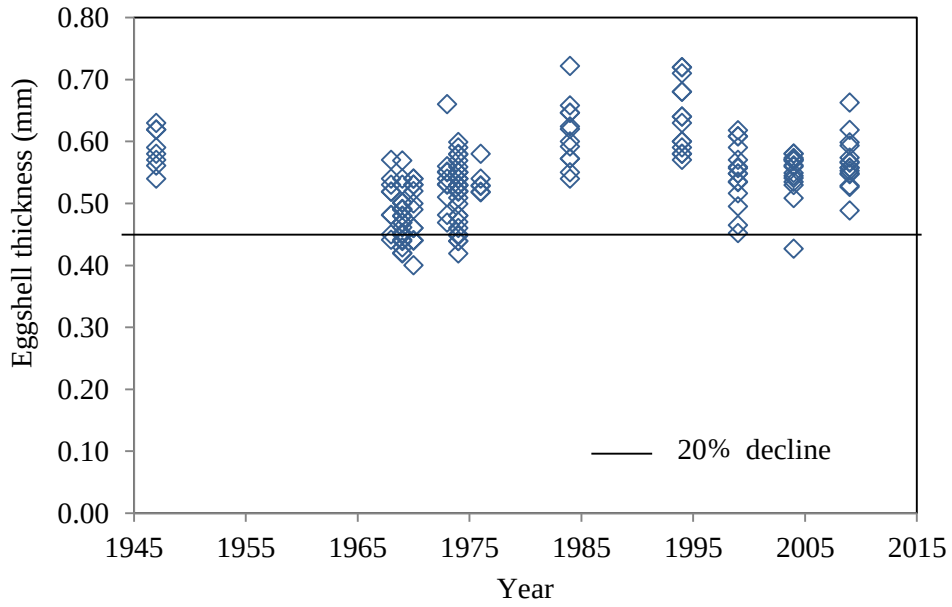

Figure 16. Eggshell thickness of Northern Gannet eggs from Bonaventure Island. The line represents a 20 % decline in eggshell thickness relatively to the reference years (pre-1947).

3.4.4 Stable isotopes

There are significant year differences in the $\delta^{15}N$ ($F_{8,16} = 7.2$; $p = 0.006$) and $\delta^{13}C$ ($F_{8,16} = 16.1$; $p < 0.001$) values (Table 17). The linear regressions indicate a negative temporal trend in $\delta^{13}C$ ($F_{1,16} = 11.5$; $p = 0.004$) but not in $\delta^{15}N$ ($F_{1,16} = 1.4$; $p = 0.25$; Figure 17). However, when the $\delta^{13}C$ values are corrected to take account of the Suess effect, the relationship becomes non-significant ($F_{1,16} = 0.35$; $p = 0.56$). Several contaminants show significant relationships with the $\delta^{13}C$ and corrected $\delta^{13}C$ values, but almost no relationship with $\delta^{15}N$ (Table 18).

Table 17. Mean values (‰ ± standard deviation) of stable isotopes of carbon and nitrogen in Northern Gannet eggs from Bonaventure Island, 1969 to 2009

Year	*nb*	$\delta^{13}C$	Corrected $\delta^{13}C$ (Suess effect)	$\delta^{15}N$
1969	1	-20.5 [a]	-20.1 [abc]	15.1 [ab]
1973	1	-20.9 [ab]	-20.5 [bc]	14.2 [c]
1976	1	-20.8 [ab]	-20.3 [abc]	14.8 [abc]
1984	1	-20.3 [a]	-19.6 [ab]	15.2 [a]
1989	1	-20.4 [a]	-19.6 [ab]	15.1 [abc]
1994	3	-20.6 [a] ± 0.2	-19.7 [a] ± 0.2	15.0 [a] ± 0.1
1999	3	-20.7 [a] ± 0.1	-19.8 [ab] ± 0.1	14.5 [abc] ± 0.2
2004	3	-21.4 [b] ± 0.1	-20.4 [c] ± 0.0	14.4 [bc] ± 0.2
2009	3	-21.4 [b] ± 0.2	-20.3 [c] ± 0.2	14.7 [abc] ± 0.1

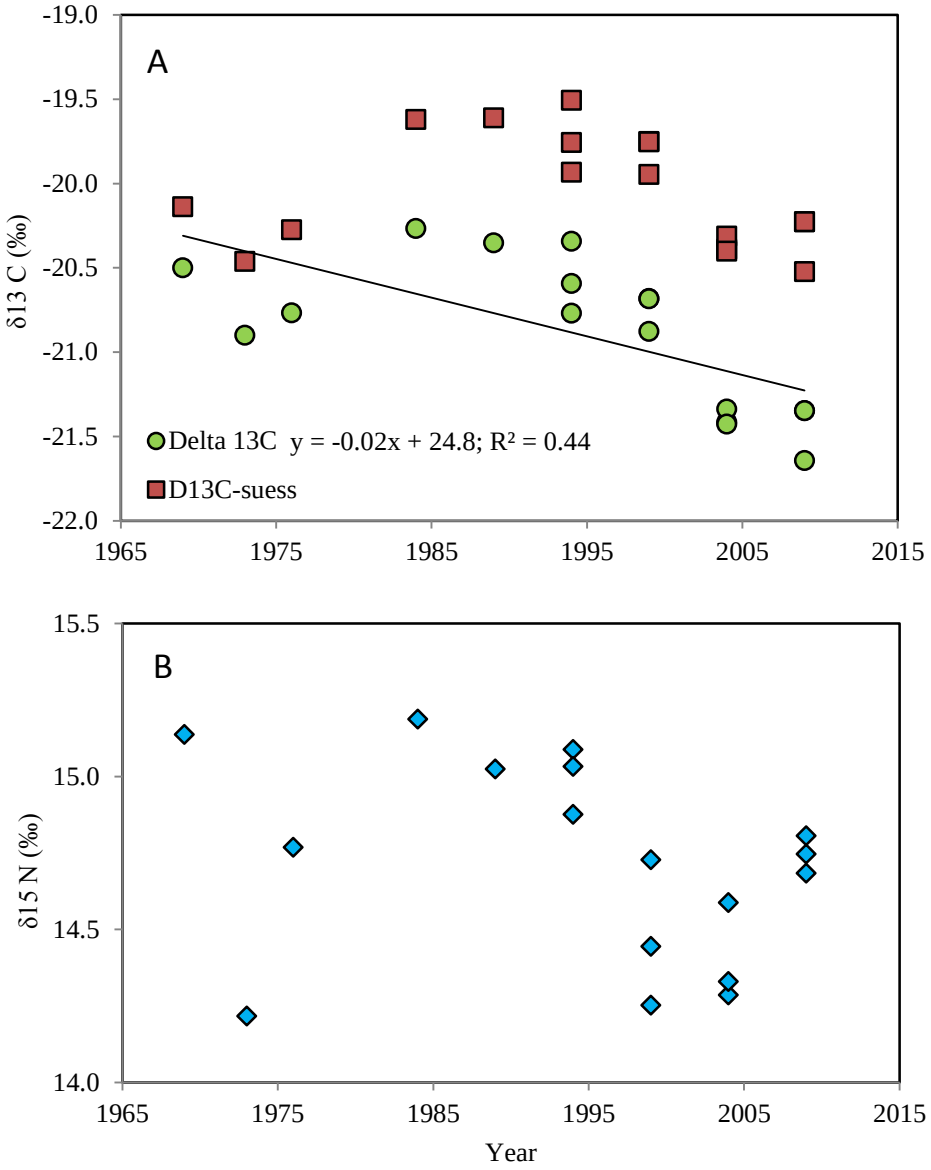

Figure 17. Temporal trends of stable isotopes of A) carbon (δ^{13}C) and B) nitrogen (δ^{15}N) nitrogen in Northern Gannet eggs from Bonaventure Island, 1969 to 2009.

Table 18. Spearman's correlation coefficients between eggshell thickness, stable isotopes of carbon and nitrogen and contaminants in Northern Gannet eggs from Bonaventure Island[1]

Contaminant	Eggshell thickness	$\delta^{13}C$		Corrected $\delta^{13}C$		$\delta^{15}N$	
Mercury	0.035	0.615		0.185		0.169	
PCB-118	0.410	0.840	*	0.835	*	0.515	
PCB -138	0.477	0.848	*	0.852	*	0.585	
PCB -153	0.230	0.826	*	0.857	*	0.446	
PCB -180	0.481	0.820	*	0.868	*	0.679	
PCB -187	0.442	0.441		0.533		0.795	*
PCB -206	-0.141	0.042		0.069		0.011	
1-ortho	0.240	0.815	*	0.805	*	0.341	
2-ortho	0.424	0.820	*	0.852	*	0.643	
3-ortho	0.392	0.692		0.735		0.726	
4-ortho	0.007	0.856	*	0.766		0.169	
Tri- PCB	0.406	0.845	*	0.877	*	0.429	
Tetra- PCB	0.290	0.859	*	0.785	*	0.266	
Penta- PCB	0.396	0.862	*	0.874	*	0.471	
Hexa- PCB	0.414	0.820	*	0.835	*	0.623	
Hepta- PCB	0.452	0.753		0.796	*	0.729	
Octa- PCB	0.163	0.865	*	0.760		0.266	
Nona- PCB	-0.141	0.042		0.069		0.011	
Total PCB (38 cong.)	0.269	0.806	*	0.841	*	0.549	
PCB 1:1	0.243	0.738		0.108		0.503	
α-HCH	-0.362	0.557		-0.230		-0.007	
β-HCH	-0.207	-0.016		-0.665		0.150	
Total HCH	-0.598	-0.040		-0.514		-0.187	
pp'-DDT	-0.069	0.301		-0.481		0.436	
pp'-DDD	-0.129	0.745		-0.087		0.328	
pp'-DDE	0.186	0.771	*	0.102		0.444	
Total DDT	0.166	0.765		0.087		0.451	
trans-nonachlor	0.435	0.798	*	0.677		0.518	
cis-nonachlor	-0.285	0.782	*	-0.060		0.283	
Oxychlordane	-0.512	0.532		-0.390		0.083	
cis-chlordane	-0.178	0.740		-0.098		0.332	
trans-chlordane	-0.209	-0.115		-0.477		0.033	
Heptachlor epoxide	0.193	0.758		0.123		0.535	
Total chlordane	-0.038	0.449		-0.209		0.272	
Dieldrin	0.153	0.710		0.050		0.414	
photo-Mirex	-0.119	0.304		0.333		0.093	
Mirex	0.168	0.775	*	0.133		0.508	
HCB	0.008	-0.201		-0.358		0.176	
OCS	0.512	0.788	*	0.803	*	0.743	
TCPM	0.403	-0.389		-0.310		0.288	
Total OC	0.188	0.739		0.062		0.466	

[1] (n = 19). The signification level of the correlations is indicated when $p < 0.001$ (*).The signification level α has been corrected with the Bonferroni method for the number of tests done (41 contaminants ; $\alpha = 0.05 / 41 = 0.001$).

4 DISCUSSION

4.1 POPULATION SIZE IN QUEBEC

Northern Gannet numbers in Quebec grew steadily between 1976 and 2009, and the present population is large. Although the occupancy rate of suitable cliff ledge sites must be approaching saturation at the three colonies, the plateaus on the main island at Bird Rocks and on Bonaventure Island contained enough quality habitat to support continued expansion of the colonies until 2009. Growth of the Bird Rocks colony can be expected to slow down in the near future, given the annual decrease in the available nesting space on the plateau.

In 2009, the 3 colonies in the Gulf of St. Lawrence contained nearly 90 000 breeding pairs of Northern Gannets. The total Gulf population has not been this large since before 1860. Fisher and Vevers (1943) estimated that in 1833 (when Audubon reported that Bird Rocks was completely covered with gannet nests) there were between 100 000 and 125 000 breeding pairs on Bird Rocks. Their estimate even took into account the surface area of the main rock, which has declined considerably since then due to erosion. In the past, the Bird Rocks colony was intensively exploited, with gannet flesh being harvested by fishers for bait. In 1860, Bryant (1861) noted that only half of the plateau on the main island was occupied by nests. At the time he estimated the Bird Rocks population to be 75 000 pairs. A lighthouse was subsequently built and occupied in 1869. Around 1900, the Gulf population likely reached a historic low of about 5000 breeding pairs. Fisher and Vevers (1943) reported that there were about 1500 pairs on Bird Rocks in 1904 and 3500 pairs on Bonaventure Island in 1898 (one of the first estimates for this colony); they also indicated that the Ile aux Perroquets colony (Mingan) had disappeared around 1900 and the Falaise aux Goélands colony (Anticosti Island) probably wasn't established until the 1910s. Gannet numbers remained low during the first half of the 20th century.

It was not until the 1960s that the two main colonies began to expand rapidly, with the number of breeding pairs exceeding 5000 on Bird Rocks and 20 000 on Bonaventure Island. In the 1970s, because of the effects of DDT present in the environment on gannet breeding success, a reverse trend emerged and a slight decrease in population size was observed (Chapdelaine et al. 1987). In the late 1970s when DDT concentrations in gannet eggs began falling sharply, reproductive success in both colonies returned to normal levels. The colonies began expanding again and showed no signs of slowing.

The Bonaventure Island colony grew at an annual rate of about 3 to 4% a year for nearly 25 years (between 1976 and 1999). The rate of growth even accelerated between 1999 and 2004, which was surprising considering the colony's size. According to Moss et al. (2002) at least, the growth rate of a

Northern Gannet colony (generally is and) theoretically should be inversely proportional to the size of the colony. Between 2004 and 2009, however, the rate of expansion slowed considerably and fell to a level not seen since 1976. Nonetheless, in 2009 the Bonaventure Island colony appeared to still be growing, leading us to believe that it would be confirmed as the largest Northern Gannet colony in the world in the next census, which is slated for 2014, since the numbers at the St. Kilda colony in Scotland were holding steady at nearly 60 000 pairs (59 622) in 2004 (Wanless et al. 2004).

How can we explain the nearly constant growth of the Bird Rocks and Bonaventure Island colonies between 1979 and 2009, given the finding (Moss et al. 2002) that large gannet colonies grow more slowly in general relative to small colonies? First, we should compare plateau habitat and cliff ledge habitat. During the 30-year period concerned, colony expansion occurred mainly on the plateau areas. Plateaus may have been colonized more quickly because of the larger amount of available habitat and the better quality nesting sites (where breeding success is higher on average), which hold greater appeal for new breeders. Second, rapid colonization of the main island at Bird Rocks can be explained partly by the lighthouse keeper's departure from the island in 1987 (when the lighthouse became automated), which suddenly freed up undisturbed unoccupied high-quality habitat for gannet nesting, extending over the entire plateau. Such high annual growth rates (between 12 and 53% per year during the period 1976–1999 on the plateau) cannot realistically (for a species that lays only one egg) be attained solely through natural recruitment to the colony. One possible explanation is that before the island plateau area was freed from human disturbance by the lighthouse keeper's departure, a growing cohort of gannets of reproductive age frequented the colony without being able to nest there, because almost all of the best cliffside nesting sites were occupied. After 1987, these birds were able to find nesting sites on the plateau.

The potential for population expansion in the Gulf is limited in part by the available habitat. Anticosti Island never had more than 500 nests, presumably because many of the cliff ledges are too narrow or friable to accommodate a large gannet nest. On Bird Rocks, the main rock could become completely occupied over the next decade. That leaves Bonaventure Island, where area covered by vegetation and the decaying trees on the plateau is gradually shrinking (probably because of the abundant droppings and because gannets pull up the low-growing vegetation at the edge of the colony to build their nests), leaving a larger open area suitable for nesting. In addition, there is still a sizeable area of unused habitat on the plateau at the colony's periphery. It appears unlikely that other colonies will become established elsewhere in the Gulf, considering that historically only one other site in the Gulf is known to have been home to a Northern Gannet colony, specifically Ile aux Perroquets in the Mingan Archipelago. That colony was abandoned shortly after a lighthouse was built on the island in 1888, and recent efforts deployed over 6 seasons (1997–2002) to reintroduce the species on Ile aux Perroquets met with failure

(Gummer 2003). The fact that there is no source colony in North America within a distance of 200 km has likely lessened the chance that Northern Gannets will recolonize this site (Jones and Kress 2012). The likelihood of immigration from Europe is even lower, given the limited exchanges that occur between these two populations (Gaston et al. 2008).

Furthermore, even with new nesting sites, gannet numbers could not keep growing indefinitely in the Gulf of St. Lawrence. Taking into consideration the relative precision of the estimates, the 2009 census identified Bonaventure Island as the largest Northern Gannet colony in the world, on an equal footing with the St. Kilda colony in Scotland, which had just under 60 000 pairs (59 622) (Wanless et al. 2004). This raises an important question. What is the maximum size that a Northern Gannet colony or the Gulf of St. Lawrence population could reach before density- or colony size-dependent effects would occur, such as increased competition for food resources (Lewis et al. 2001; Elliott et al. 2009)? When the population size approaches the carrying capacity of the environment, breeding success can be affected, along with the growth and survival of both chicks and adults. All of these factors can ultimately affect the population trend.

Finally, although the population trend in Quebec over the past 40 years seems to be tied to reproductive success, a variety of other factors may also affect the health or survival rate of immatures and adults. Populations of long-lived species that lay only one egg, like the Northern Gannet, are very sensitive to a decrease in the adult survival rate. Poor weather conditions, changes in climatic and ocean conditions, a decrease in the abundance or availability of food, by-catch in fishing nets, contaminants and oil spills—all of these threats have the potential to cause significant harm to the population not only during the breeding period, but also during migration or wintering, all along the east coast of North America and in the Gulf of Mexico (see Montevecchi et al. 2012).

4.2 PRODUCTIVITY ON BONAVENTURE ISLAND

The overall estimate of Northern Gannet breeding success on Bonaventure Island in 2004 (72.9% of pairs that laid an egg fledged their chick) was very close to the mean for the period 1976 to 1999 (73.3% ± 2.5%), which was characterized by a fairly constant rate of reproductive success. This represents a fairly high rate of productivity, well above the values (about 30%) observed in 1966–1967 and 1970, when the colony was in decline, and higher than the net productivity threshold of 67% considered necessary to ensure the colony's stability (Chapdelaine et al. 1987). In 2005, the colony's net productivity (67.8%), which was about 5% lower than the previous year both on the plateau and on the cliff face, was the lowest rate recorded since 1974, but represented a level of reproductive success theoretically permitting maintenance of (but not an increase in) colony size over the long term.

Following the period of high DDT contamination that adversely affected Northern Gannet reproduction in the late 1960s and the early 1970s, hatching success and fledging success remained stable and high (means of 81.9 and 88.8% respectively) for a period of nearly 30 years, from 1976 to 2005. In 2009 hatching success (57.7%) was nearly 24% lower than the mean for 1976 to 2005, and 17% below the lowest value measured during that period. Fledging success, which stood at 83.7% in 2009, was only 5% below the mean for 1976 to 2005. Very low hatching success, combined with below-average fledging success, explains the low net productivity observed in 2009, when only one chick fledged for every two pairs that produced an egg (or 0.5 chick/pair with an egg). Such a low level of productivity (nearly 20% below the lowest values recorded between 1976 and 2005) would not support sufficient recruitment to allow the Bonaventure Island colony to maintain itself over the long term.

In short, after a long period during which breeding success remained at high levels, allowing the Bonaventure Island colony to expand quickly, the 2005 and especially 2009 surveys yielded the lowest values seen since the 1970s. Future research may be able to determine whether the much lower productivity recorded for the colony in 2009 was a one-off event or whether it actually reflects a downward trend. Since breeding success was fairly high until 2004, and since Northern Gannets start breeding at five years of age, there was no reason to expect a decline in the number of breeders before 2009. If reproductive success actually began to decline in 2005, the effects of lower recruitment (cessation of growth or decline in the Bonaventure Island colony) will not become apparent until more five-year surveys are carried out.

Furthermore, the reduced productivity recorded in 2009 was mainly the result of very low hatching success, given that fledging success was only slightly below the 30-year average. There was a much greater difference in breeding success between the cliff face and the plateau in 2009. Hatching success and fledging success were very low on the cliff face in 2009, giving a productivity level of 25% (1 chick fledged for every 4 eggs laid), which is more than 30% lower than the productivity level on the plateau. At present, we cannot identify the factors that affected breeding in 2009 with certainty. We can, however, deduce that, given the very low hatching success in 2009, the causes of the low productivity recorded that year were particularly significant at the start of the season, that is, during the incubation period. Several naturalists working for the Parc national de l'île Bonaventure-et-du-Rocher-Percé mentioned that the weather conditions were terrible at the start of the summer, with extended periods of heavy rainfall and cold temperatures. Some previously occupied sectors on the plateau appear to have been deserted; the nests were likely washed away by the heavy rainfall. It is logical to think that the rain took an even greater toll on the cliffside nests, since water from the plateau washes down the cliff face. This could explain the much lower productivity of the cliffside nesting sites.

Some unusual observations were reported in 2009, such as flooded nests with the egg or chick sitting in water, and adults shivering from the cold. Many chicks died at a young age. Nonetheless, the weather conditions eventually improved and, in late summer, the chick survival rate (fledging success) was only slightly below normal. Most of the chick mortality occurred prior to July 23, that is, in the first weeks after hatching, whereas from late July to early September about 90% of the chicks survived.

The year 2009 may have been an exceptionally bad year because of the weather conditions, rather than part of a trend that will become accentuated over the coming years. However, the climate change currently underway is very likely to lead to more frequent extreme weather events, including more frequent episodes of heavy precipitation (IPCC 2007). The weather conditions that marked the summer of 2009 may not appear so unusual in the future. Furthermore, climate change will affect marine ecosystems (IPCC 2007), with potential consequences for gannets' prey species (Montevecchi and Myers 1997; Montevecchi 2007; Gaston et al. 2009). Changes could occur in the availability of food resources or in the distribution and migration of forage fish (see Section 4.3). In addition, it may become more difficult to manage the stocks of some commercially fished species if they are subject to sudden and unpredictable changes in abundance (FRCC 2009). Since the Northern Gannet already devotes a great deal of effort to reproduction (feeding of young extends over a long three-month period), a decrease in prey abundance could have a major impact on this species' breeding success and even breeding propensity.

In addition to weather conditions, food abundance and contaminants (see Section 4.4), predation could also affect the reproductive success of the Bonaventure Island colony. A number of Red Foxes (*Vulpes vulpes*) live on the island, and every year Bald Eagles (*Haliaeetus leucocephalus*; immatures and adults) are observed near the colony. Although the presence of these predators has not hindered colony expansion to date, foxes have often been seen taking eggs or young at the edge of the colony, and non-breeding gannets sometimes panic when a Bald Eagle flies over the colony. The increased presence of these predators near the colony or an increase in their numbers could interfere with nesting (the same is true for Bald Eagles on Anticosti Island, since they are fairly abundant).

4.3 GANNET DIET ON BONAVENTURE ISLAND

In 2004, 2005 and 2009, the main observation made concerning the gannet diet was that the birds nesting on Bonaventure Island during the summer fed mainly on mackerel and herring. Previous studies conducted on Bonaventure Island reported similar findings (Poulin 1968, Lafleur 1969, Rail et al. 1996, and see the unpublished CWS data in Appendix 6), except the study by Taylor and Nettleship (1974), which reported that very little herring was found in gannet regurgitations in the summer of 1974. At the Bird Rocks colony (Magdalen Islands), the gannet diet is likewise dominated by mackerel beginning in

July, but it is complemented primarily with Sand Lance, and herring is absent (Burton 1980). At the Funk Island colony on the east coast of Newfoundland, studies conducted between 1977 and 1986 (Kirkham et al. 1985; Montevecchi et al. 1988) showed that mackerel was the main prey of gannets, followed by Capelin and Northern Shortfin Squid (*Illex illecebrosus*; Montevecchi et al. 1988). A major change was subsequently observed, with Capelin replacing mackerel and squid almost completely (Montevecchi and Myers 1996; Montevecchi et al. 2009).

Northern Gannets are opportunistic predators and their diet reflects the availability of food resources. For example, on Funk Island, the gannet diet shift from warm-water prey such as mackerel, squid and saury to cold-water fish (Capelin) was linked to an oceanographic anomaly: cold surface waters observed in the 1990s likely inhibited the movement of migrant warm-water species to the inshore regions of the North Atlantic (Montevecchi and Myers 1996). In addition, annual and seasonal variations in prey abundance like those reported in fisheries data are reflected in the gannet diet (Montevecchi and Myers 1995, Montevecchi et al. 2009). At Bonaventure Island in 2009, the unusual abundance of Capelin in mid-July and the sudden appearance of saury in the gannet diet in September were indicative of changes in the seasonal abundance patterns and distribution (respectively) of these prey species that year. Future studies on the gannet diet could make it possible to determine whether a trend is emerging or whether the changes in prey observed in 2009 were anomalies.

Studies on the gannet diet have described substantial seasonal variations. Lafleur (1969) reported that herring is an important component of the diet at the Bonaventure Island colony during two periods: during the early part of the season (until July 4) and then from August 10 to 24. These periods correspond to the two herring spawning periods. Mackerel appear to arrive between June 17 and 24 and are present in regurgitations from that point on (Lafleur 1969). Taylor and Nettleship (1974) mentioned that Capelin were abundant only until June 19. Because we never sampled regurgitations on Bonaventure Island earlier than the month of July, the results presented in this report cannot shed light on the relative importance of Capelin and herring at the start of the season (in May and June). Mackerel is normally the main prey species from July to September. However, on September 1, 1999, September 8 and 9, 2004, and August 18 and 19, 2005, herring dominated the gannet diet; these dates may correspond to a second spawning period. In addition, with the exception of July 11 and 12, 2009, we found that Capelin was not an important component of the gannet diet from July to September. This small fish species is undoubtedly a common dietary item at the start of the season (May to June), particularly during Capelin spawning, when aggregations of thousands of gannets can be seen on a regular basis circling overhead and then diving into the shoals of Capelin, very close to the shores of Percé.

One might wonder how the Northern Gannets in Quebec would be affected by a decrease in the abundance of some of their preferred prey species or by a change in these species' migration patterns or distribution. The Gulf of St. Lawrence, like other marine ecosystems around in the world, is currently affected by changes in oceanographic conditions (physical, chemical and biological components), which may accelerate with climate change (Benoît et al. 2012). In addition to prey availability over time, it is important to consider the vertical and horizontal distribution of prey, given that the maximum dive depth of gannets is 20 m (Garthe et al. 2007), a level below which prey become inaccessible. Even though these birds are opportunists and feed on a variety of prey, in May and June herring and Capelin appear to be important prey items until the arrival of warm-water migrant species such as mackerel, squid and saury. From July to September, however, when Capelin and herring are less available (although herring are present for a short period) because they probably remain farther down in the water column, the adult gannets' energy demands are enormous since they have young chicks to feed. At this time, the presence of mackerel appears to be of paramount importance. Owing to its large size and high lipid content, mackerel is the most energy-dense prey eaten by Northern Gannets (Montevecchi et al. 1984).

In spite of the limited amount of information available for accurate stock assessments, the data analyzed by Grégoire et al. (2009) show that mackerel abundance has decreased since 2005 in the southern Gulf (where mackerel abundance is greatest). Furthermore, 1999 appears to have been the last good spawning year for mackerel. Because this strong year-class (which represented the bulk of mackerel landings in the early 2000s) is now fast disappearing, the authors do not think that the catch levels of the recent past will be sustainable over the coming years. Changes in mackerel migration and distribution have also been noted, which may be attributable to the unusual oceanographic conditions of recent years, specifically the colder surface water temperatures (Grégoire et al. 2009). In summary, regardless of the cause—a decrease in prey availability due to fishing-related mortality, poor spawning years or changes in distribution or migration associated with altered ocean or climatic conditions—short- and medium-term variations are likely to occur in mackerel abundance in the Gulf of St. Lawrence, and this could adversely affect Northern Gannets during the breeding season.

With regard to the current status of herring, a distinction must be made between two stocks—one that spawns in the spring and the other in the fall. Whereas in the southern Gulf of St. Lawrence, the fall spawning stock is considered to be in the healthy zone (the exploitation rate is acceptable relative to stock status), the abundance of spring spawners is cause for concern to say the least, because it has decreased substantially since 1995 and is close to the historical low (FRCC 2009). In the northern Gulf, herring abundance has always been lower and Capelin tends to be the dominant forage species (FRCC 2009). Herring is another species that is subject to large and rapid changes in abundance, and that is difficult to

manage. In spite of the management measures implemented and considerable regulation, there have been many instances of herring fishery collapse elsewhere in the world. In each of these cases, stock collapse was very rapid, and stock recovery has been slow (FRCC 2009). The herring stocks of the Gulf of St. Lawrence therefore do not appear to be immune to future variations in abundance, whether they are associated with fishing mortality or to changes in environmental conditions. Herring availability in the Gulf, particularly before the arrival of mackerel in July, probably plays an important role in ensuring the breeding success of Northern Gannets.

Capelin are especially abundant in the northern part of the Gulf, around Anticosti Island and off the west coast of Newfoundland. In the 1990s, a southward extension in distribution occurred in association with below-normal water temperatures (Frank et al. 1996), but an inverse trend was noted between 2004 and 2007 (Grégoire et al. 2008). Capelin has not been the target of intensive commercial fishing in the Gulf of St. Lawrence to date, hence catch levels have not had noticeable effects on the Capelin population (Grégoire et al. 2008). Overfishing of predators of Capelin (including cod) has likely benefited this species and allowed it to thrive (Frank et al. 2005). However, given the limited amount of data obtained from the fisheries, considerable uncertainty exists about Capelin abundance, and little is known about Capelin spawning grounds. Because the species has a short life span (four to five years), its abundance is subject to abrupt changes (Grégoire et al. 2008).

4.4 CHEMICAL ANALYSES ON BONAVENTURE ISLAND

4.4.1 Mercury and inorganic elements

Concentrations and toxicity thresholds

Mercury concentrations in eggs are below the levels associated with effects on survival or reproduction, which corresponds to concentrations ranging from 0.8 to 5.1 mg/kg ww (Thompson 1996; Shore et al. 2011). Mercury levels in gannet eggs in 2009 were similar to or higher than those in the eggs of other piscivorous bird species that nest in the St. Lawrence estuary (Great Blue Heron [*Ardea herodias*] and Black-crowned Night Heron [*Nycticorax nycticorax*] (Champoux et al. 2002; Champoux et al. 2006)); in the Gulf of St. Lawrence (Great Black-backed Gull [*Larus marinus*] and Herring Gull [*L. argentatus*], Black-legged Kittiwake [*Rissa tridactyla*], Razorbill [*Alca torda*] and Black Guillemot [*Cepphus grylle*] (Lavoie et al. 2010)); along the Atlantic coast (Arctic Tern [*Sterna paradisaea*], Atlantic Puffin [*Fratercula arctica*], Common Murre [*Uria aalge*], Common Tern [*Sterna hirundo*], Leach's Storm-Petrel (*Oceanodroma leucorhoa*), Razorbill (Bond and Diamond 2009a, b) and Herring Gull (Burgess et al. 2013)); in the Arctic (Black-legged Kittiwake, Northern Fulmar [*Fulmarus*

glacialis] and Thick-billed Murre [*U. lomvia*] (Braune 2007)); and on the Great Lakes (Herring Gull (Koster et al. 1996)). However, in the Great Lakes region, higher concentrations have been reported for a number of species (Herring Gull, Black-crowned Night Heron, Great Black-backed Gull, Black Tern [*Chlidonias niger*], and Forster's Tern [*Sterna forsteri*] (Jermyn-Gee et al. 2005)). In the Gulf of Maine, mean mercury levels were measured in the eggs of 12 bird species, and found to range from 0.04 to 0.62 mg/kg ww for the Glossy Ibis (*Plegadis falcinellus*) and Leach's Storm-Petrel, respectively (Goodale et al. 2008). Between 1974 and 2004, the mercury concentrations measured in Northern Gannet eggs from Bonaventure Island were similar to or lower than those measured in two gannet colonies in Great Britain (Pereira et al. 2009).

While cadmium (Cd) and lead (Pb) are generally present at low levels in bird eggs (Scheuhammer 1987; Leonzio and Massi 1989), the concentrations of copper (Cu) and zinc (Zn), which are essential elements, are below the no-observed-effect level (Stronkhorst et al. 1993). The selenium (Se) levels in gannet eggs were lower than the threshold (10 mg/kg dw), beyond which adverse effects may be observed in Mallards (*Anas platyrhynchos* (Heinz 1996)). Ohlendorf and Heinz (2011) reported that a low probability for reduced egg hatchability exists for Se concentrations below 8 mg/kg dw and an elevated probability exists for concentrations greater than 12 mg/kg dw, in sensitive or moderately sensitive species.

With regard to trace element concentrations, gannet eggs were found to have copper (Cu), selenium (Se) and zinc (Zn) levels similar to those in three Canadian Arctic seabird species (Braune and Simon 2004; Braune 2007). Gannet eggs contained slightly higher Cu, Mn, Se, and Zn concentrations than the eggs of three Arctic-breeding shorebird species (Hargreaves et al. 2010). Trace element concentrations in gannets were lower (Mn), similar (Hg) or higher (As, Se) than those found in five species that nest in New Jersey (Burger 2002), and lower (Mn) and higher (Hg, Se) than the levels found in Herring Gulls breeding in the state of New York (Burger and Gochfeld 1995).

Since trace elements in gannet eggs were only analyzed in 2009, no trend could be calculated. In Herring Gulls in the state of New York, Se and Pb levels decreased between 1989 and 1994, but no other metals (Cr, Hg, Cd, Mn) exhibited a clear trend (Burger and Gochfeld 1995).

Comparison of temporal trends with other species/sites

The mercury concentrations measured in eggs from the Bonaventure Island colony showed an annual decrease of 0.3% from 1969 to 2009, for a total decrease of 12% over this 40-year period. Few contaminant trend studies are available, and most of them show an increase in mercury in seabird tissues over time.

In Scotland, two gannet colonies exhibited differing temporal trends in Hg concentrations, with a significant decrease at one colony (Ailsa Craig), located on the eastern Atlantic, and a slight increase at the other colony (Bass Rock), located on the North Sea (Pereira et al. 2009). In Canada, Braune (2007) observed an increase in egg mercury concentrations for Thick-billed Murres and Northern Fulmars in the Arctic Ocean, but she detected no trend for Black-legged Kittiwakes in the Arctic. Burgess et al. (2013) found a positive temporal relationship for Herring Gull eggs at a Newfoundland colony, but no trend at the other colonies of this species in the Atlantic or at a colony in the St. Lawrence estuary. Conversely, Koster et al. (1996) and Weseloh et al. (2011) found a negative temporal trend in mercury concentrations in Great Lakes Herring Gull eggs between 1973 and 2009. Although the range of mercury concentrations found in this gull species is very similar to that in the present study, the mercury levels decreased more sharply in Herring Gull eggs on Lake Ontario than in gannet eggs (Weseloh et al. 2011). However, the decline in gull eggs was largely attributable to changes in the species' diet.

Although mercury emissions from anthropogenic sources have increased on a global scale in recent decades, notably in Asia, they have declined in North America and Europe over the past decade (UNEP Chemicals Branch 2008). This likely explains why a negative temporal trend in mercury has been found in avifauna on the Great Lakes and in the St. Lawrence, whereas positive trends have been observed in other parts of the world.

4.4.2 Polychlorinated biphenyls, dioxins and furans

Concentrations and toxicity thresholds

PCBs, dioxins and furans are families of persistent organic pollutants that are structurally related and have similar properties. The main sources of dioxins are pentachlorophenol, used as a wood preservative, municipal incinerators and pulp and paper mills that use chlorine bleaching (Government of Canada 1990). PCBs are the main source of furans.

Over the same time period, the PCB concentrations in gannet eggs at the Bonaventure Island colony were, for the most part, higher than those in seabird eggs from the Arctic (Braune 2007) and in British Columbia (Harris et al. 2005); similar to those in seabird eggs from the estuary and Gulf of St. Lawrence (Pearce et al. 1989); and lower than those in colonial nesting waterbirds in the Great Lakes (Ewins et al. 1994; Hebert et al. 1999a; Jermyn-Gee et al. 2005; Weseloh and Moore 2009). In Scotland, the concentrations of PCB 118, 138, 153 and PCB 180 in eggs at two gannet colonies were similar to or lower than those at the Bonaventure Island colony (Pereira et al. 2009).

Dioxin and furan concentrations in gannet eggs from the St. Lawrence are higher than those in Great Blue Heron eggs at colonies along the St. Lawrence (Champoux et al. 2009) and similar to those in Great Blue Heron eggs along certain regions of British Columbia (Elliott et al. 2001). The dioxins and furans measured in British Columbia were dominated by penta- and hexa-chloro-dibenzodioxins, with toxic equivalent concentrations remaining high due to contributions from PCBs at some urban colonies (Elliott et al. 2001). At most heron colonies along the St. Lawrence, penta- and hexa-CDDs were likewise dominant. In the case of Northern Gannets, 2,3,7,8-TCDF accounted for 44 and 47% of total dioxins and furans in 2004 and 2009, respectively.

In the present study, the non-ortho-PCBs were measured in gannet eggs for the first time in 2004. Although present at low concentrations compared with the other PCB congeners, their high toxicity, which is equivalent to that of dioxins and furans, explains their contribution of 72 and 77% to the toxic equivalent in 2004 and 2009, respectively. Other published studies (Kannan et al. 2001; Braune et al. 2007; Champoux et al. 2009) also mentioned the predominant contribution of non-ortho-PCBs to the toxic equivalent, along with the dominance of PCB congener 126 relative to the other non-ortho-PCBs.

Harris and Elliott (2011) reviewed the most recent studies on the toxicity of PCBs, dioxins and furans and collated the data with a view to proposing effect levels. Tolerant species such as waterbirds showed reduced hatching success at total PCB levels of 23 to 142 mg/kg egg ww, whereas the critical level for alteration of parental care was found to be between 1 and 30 mg/kg egg ww (Harris and Elliott 2011). For dioxins and furans, the following embryotoxicity thresholds were established for eggs: furan levels of 1 to 3 μg/kg ww, TCDD levels of 1 to 11 μg/kg ww, and PCB-126 levels of 24 to 158 μg/kg (ww) (Harris and Elliott 2011). These values exceed the concentrations measured in gannets in the present study.

Comparison of temporal trends with other species/sites

In Scotland, gannet eggs collected at the Ailsa Craig colony showed a decline in all PCB congeners between 1977 and 1998 (Alcock et al. 2002). Although the PCB concentrations were lower, the rate of decrease was slightly higher, and the half-lives shorter, for congeners in eggs at Ailsa Craig compared to Bonaventure Island. This can be explained by the fact that Alcock et al. (2002) measured congeners in archived eggs for the entire 1977–1992 period, whereas the analysis of congeners in the present study covers the period beginning in 1989. Likewise at the Ailsa Craig colony (Atlantic side), and at the Bass Rock colony (North Sea side), Pereira et al. (2009) noted a decrease in PCB 138 at both colonies from 1990 to 2004, whereas PCB 118 only decreased at Ailsa Craig, and PCB 153 and PCB 180 did not show a trend at either colony. In the present study, the less chlorinated (lighter) compounds showed a more rapid decrease than the more chlorinated (heavier) ones in gannet eggs, with a more gradual slope as the degree of chlorination increased (tetra > penta < hexa and hepta). The same pattern was observed in gannets in Scotland (Alcock et al. 2002, Pereira et al. 2009), in Herring Gulls on the Great Lakes between 1971 and 1982 (Hebert et al. 1999b), and in eggs of Northern Fulmars, Black-legged Kittiwakes and Thick-billed Murres in the Arctic between 1975 and 2003 (Braune 2007). These differences in slope can be attributed to the longer half-life of the more chlorinated compounds relative to the less chlorinated ones, which is itself due to the increase in the octanol-water partition coefficient (K_{ow}; measure of the potential for bioaccumulation and biomagnification and the level of persistence of a contaminant) with increasing chlorination of PCBs (Hebert et al. 1999b; Fisk et al. 2001). Compared to the findings of Elliott et al. (1988), the half-life of PCB 1:1 in gannet eggs at the Bonaventure Island colony remained almost unchanged, indicating that PCB levels continued to decline at approximately the same rate (Appendix 8). The half-life of total PCBs (ΣPCB_{38}), as well as of the congeners and groups, was two to three times greater than that of total PCBs in the eggs of Herring Gulls on the Great Lakes from 1971 to 1982 (Hebert et al. 1999b, Appendix 8). At the Ailsa Craig colony in Scotland, the half-life of PCB 118 changed little over time, the half-life of PCB 138 decreased by half between the two studies (Alcock et al. 2002, Pereira et al. 2009), and that of PCB 153 nearly doubled (Appendix 8).

4.4.3 Organochlorine pesticides (OCs)

Concentrations and toxicity thresholds

In the past, a number of birds and other animals were poisoned by dieldrin; however, according to Elliott and Bishop (2011) there is little evidence of sublethal effects. These authors propose a threshold of 1 mg/kg in eggs as the level beyond which effects may appear. Chlordane is a mixture composed primarily of *cis*- and *trans*-chlordane, heptachlor and *cis*- and *trans*-nonachlor; oxychlordane and heptachlor epoxide are associated metabolites (Elliott and Bishop 2011). Heptachlor epoxide

concentrations of 10 and 1.5 mg/kg in eggs have been linked to reduced breeding success in Canada Geese (*Branta canadensis*) and American Kestrels (*Falco sparverius*), respectively (Blus et al. 1984; Elliott and Bishop 2011). The concentrations of dieldrin and chlordane measured in Northern Gannets are lower than these thresholds. The other OCs are found at low concentrations.

Comparison of temporal trends with other species/sites

The levels of a number of organochlorine contaminants declined in eggs at the Bonaventure Island colony between 1969 and 2009. These trends are consistent with those reported in earlier research (1968 to 1984) concerning the same population, which showed a significant decrease in most organochlorine contaminants (Chapdelaine et al. 1987; Elliott et al. 1988). Elliott et al. (1988) found that heptachlor expoxide and mirex were the only contaminants that did not show a significant decrease, while α-HCH appeared to increase. By contrast, the present study showed a significant decline in those 3 compounds. The most notable change observed in gannet eggs, that is, a decrease of 99.4% in *p,p*'-DDE between 1969 and 2009 is similar to the 97% decrease recorded in Herring Gulls on Lake Erie between 1974 and 2005 (Weseloh and Moore 2009). The half-life of *p,p*'-DDE has increased slightly since the study conducted by Elliott et al. (1988), indicating a slower rate of decline (Appendix 8). In addition, the half-life of dieldrin has increased, and the half-life of chlordanes has decreased since the study by Elliott et al. (1988).

Decreases in organochlorine contaminants were also measured in eggs of Double-crested Cormorants (*Phalacrocorax auritus*), Atlantic Puffins and Leach's Storm-Petrels collected from certain colonies in Quebec, New Brunswick and Newfoundland between 1968 and 1984, with the largest decline being observed in DDE (Pearce et al. 1989). Differences were noted, however, among species and sites. For example, the concentrations of DDE, PCB and dieldrin did not decrease significantly in Double-crested Cormorant eggs at one colony in the St. Lawrence estuary (Ile aux Pommes) in Quebec (Pearce et al. 1989). In general, the rate of decline was more pronounced for DDT than for total PCBs (Elliott et al. 1988; Pearce et al. 1989). We noted the same pattern in our study, with a more pronounced decline in most organochlorine compounds than in most PCB congeners. The rate of decline for most of the organochlorine contaminants was faster than in the Arctic (Braune 2007) but slower than in British Columbia (except for DDE; Harris et al. 2005). A decrease in the levels of several organochlorine contaminants such as PCBs and mirex was observed in Herring Gull eggs on the Great Lakes (Comba et al. 1993; Hebert et al. 1999a); it coincided with an improvement in their reproductive success (Hebert et al. 1999a). As of the early 1980s, however, a slower rate of decrease was observed in OCs, particularly in PCBs in Herring Gulls on the Great Lakes (Pekarik and Weseloh 1998; Hebert et al. 1999a; Weseloh and Moore 2009). A study conducted in western Canada on Double-crested Cormorants and Pelagic Cormorants (*Phalacrocorax pelagicus*) also showed a reduced rate of decline between 1970 and

2003 (Harris et al. 2005). In the present study, a similar decrease in the rate of decline of certain OCs was observed in the 1980s. It has been shown that the levels of persistent contaminants such as OCs declined rapidly after these substances were banned or their use was reduced in the 1970s. The rate of decline slowed in subsequent years as the contaminants reached lower levels approaching the detection limits (Harris et al. 2005; Hebert et al. 1999a; Weseloh and Moore 2009).

4.4.4 Brominated flame retardants

Toxicity concentrations and thresholds

Because BFRs are used in a wide range of products and are chemically similar to PCBs, they have become widespread in the environment and are bioaccumulating in food chains. They do not appear to biomagnify as PCBs do (Harris and Elliott 2011). Although knowledge about the toxicity of PBDEs and other flame retardants is limited, a few studies have shown that they have effects on bird physiology and reproduction (Harris and Elliott 2011). Laboratory (Fernie et al. 2008; Fernie et al. 2009) and field (Henny et al. 2009) studies appear to show effects on breeding success at PBDE concentrations of 1 to 2 mg/kg ww (Harris and Elliott 2011). These values, along with the estimate derived by Elliott et al. (2005), based on the daily rate of ingestion, absorption efficiency and the dietary concentration, suggest that the concentrations measured in Northern Gannet eggs in the present study are below the levels that can cause harm.

Total PBDE concentrations in gannets eggs at the Bonaventure Island colony were found to be higher than the levels in gannet eggs in Great Britain during the same period (Crosse et al. 2012), but lower than those in Herring Gulls on the Great Lakes (Norstrom et al. 2002; Gauthier et al. 2008), in Great Blue Herons in the estuary and Gulf of St. Lawrence (Champoux et al. 2010), and in Great Blue Herons, Double-crested Cormorants and Ospreys (*Pandion haliaetus*) in British Columbia (Elliott et al. 2005). The concentrations in gannets are also lower than those in several piscivorous birds in the United States (Yogui and Sericano 2009 and references included herein), but higher than those in Ivory Gulls (*Pagophila eburnea*) in the Arctic (Braune et al. 2007). BFR concentrations have been linked with the population density of urban areas and with industrial activity (Elliott et al. 2005; Jenssen et al. 2007; Yogui and Sericano 2009; Champoux et al. 2010). The concentrations of BFRs in eggs of Great Blue Herons downstream from Montréal showed a gradual decline with distance, while the concentrations in upstream colonies or in areas away from the St. Lawrence were lower (Champoux et al. 2010; Champoux, unpublished data).

The predominance of the main BDE congeners (47, 99, 100 and 153) noted in the present study was also observed in most of the studies conducted on piscivorous birds in the Great Lakes (Norstrom et al. 2002; Gauthier et al. 2008), in British Columbia (Elliott et al. 2005) and along the St. Lawrence (Champoux et al. 2010; Lavoie et al. 2010). In the present study, the proportion of

less-brominated congeners appeared to be greater in 2009 than in 2004. This trend indicates that more-brominated congeners break down into less-brominated ones (Segev et al. 2009). The opposite pattern was observed in Great Blue Herons in British Columbia between 1983 and 2002, with an increase in the proportions of BDE-100, 99 and 153 relative to BDE-47, which was historically dominant (Elliott et al. 2005). It is interesting to note that the predominant congener among total BFRs in 2009 was BDE-49, which was generally present at negligible levels in most other studies (Elliott et al. 2005; Gauthier et al. 2008; Champoux et al. 2010; Lavoie et al. 2010). BDE-49 was nonetheless detected in eggs of European Shags (*Phalacrocorax a. aristotelis* (Vetter et al. 2007)) and Northern Gannets in Great Britain (Crosse et al. 2012). The authors of this report believe that the relative abundance of this congener is an indicator of both the use of highly brominated BDEs and of its significant transformation, since BDE-49 is a potential degradation product of BDE-99.

Comparison of temporal trends with other species/sites

Temporal trends in brominated flame retardants in Northern Gannets at the Bonaventure Island colony were not calculated because these substances were only measured in 2004 and 2009. For all the congeners or sums of congeners, only one significant difference was noted between the two years, specifically for BDE-138. However, the total concentrations of BFRs and of PBDEs seem to have been lower in 2009 than in 2004. The broad range of concentrations measured in 2004 and the small sample size are certainly responsible for the lack of significant differences. PBDE concentrations in North American birds increased rapidly until the early 2000s but they have been declining since 2006 (Gauthier et al. 2008; Harris and Elliott 2011). An increase in BFRs was noted in Herring Gulls on the Great Lakes between 1982 and 2006 (Gauthier et al. 2008). The increase observed between 2000 and 2006 was not as large as the increase seen before 2000, and a decrease was even measured at certain sites (Gauthier et al. 2008). Similar trends were found in Great Blue Herons and Double-crested Cormorants in British Columbia: a marked increase was found in Great Blue Herons from 1983 to 1996, followed by a slower rate of increase or even a decline in some cases; in the case of Double-crested Cormorants, an increase was noted between 1979 and 1994, followed by a decline that lasted until 2002 (Elliott et al. 2005). In Scotland, Crosse et al. (2012) observed an increase in PBDE concentrations in gannet eggs beginning in the late 1980s and a rapid decline after 1994. The difference in temporal trends between Europe and North America reflects the different timing of regulations governing the products concerned and their withdrawal from the market on the two continents.

There is a difference between the Great Lakes and the Gulf of St. Lawrence in the pattern of distribution of PBDE congeners. Although in Lake Ontario the proportion of BDE-209 increased considerably between 1998 and 2006, this congener was not detected in gannet eggs on Bonaventure

Island. In a study of six seabird species breeding in the Gulf of St. Lawrence (Lavoie et al. 2010), only the Herring Gull, which may migrate within the Great Lakes region in winter (Pierotti et Good 1994), showed a significant proportion of BDE-209 (Lavoie, unpublished data). This difference may be attributable to a difference in PBDE sources between the two regions.

4.5 EGGSHELL THICKNESS ON BONAVENTURE ISLAND

Eggshell thinning of 15 to 20% over a certain number of years has been linked to population decline in a number of bird species (Elliott et al. 1988). In 1984, eggshell thickness in gannets breeding on Bonaventure Island returned to levels similar to those prior to the period of DDT contamination, the main factor responsible for eggshell thinning. Elliott et al. (1988) had found a significant negative relationship between eggshell thickness and DDE concentration in gannet eggs on Bonaventure Island. With the addition of data for more recent years (1989–2009), this relationship was no longer significant. After reaching a maximum level in 1994, eggshell thickness declined in 1999 and 2004 to levels lower than those for the period before DDT contamination. Fernie et al. (2009) found a significant negative relationship between eggshell thickness and several PBDE congeners as well as HBCD. Although BRF measurements prior to 2004 were not available for the present study, based on the data from other studies (Elliott et al. 2005; Gauthier et al. 2008), it is likely that BFR concentrations were higher in 1999 and they may have been linked to this thinning. Other contaminants (not measured in the present study) may have contributed to eggshell thinning from 1999 to 2004.

4.6 STABLE ISOTOPES ON BONAVENTURE ISLAND

The isotope values show a gradual decline in $\delta^{13}C$, amounting to -0.02‰ per year, for a total of -0.8‰ over 40 years. Rather than being an indicator of trophic level, carbon isotopes provide information on the carbon sources assimilated by a given predator (Peterson and Fry 1987). In marine ecosystems, benthic primary production and benthic organisms show $\delta^{13}C$ values that are higher (or less negative) than those of pelagic primary production (France 1995; Hobson et al. 1995; Lesage et al. 2001; Hobson et al. 2002). Thus, the diet of Northern Gannets could have gradually shifted towards more pelagic species (e.g., mackerel or herring). The results of the diet study suggest that there has been little change, except perhaps an increase in the proportion of Capelin in the gannet diet in 2009; however, this change, which occurred during the chick-rearing period, cannot explain the gradual change in $\delta^{13}C$ values during egg formation.

The gradual temporal decrease in $\delta^{13}C$ could be due to the increase in carbon dioxide (CO_2) emissions associated with fossil fuel burning, which leads to a decline in the heavy isotope (^{13}C) relative to the light isotope (^{12}C), thereby decreasing overall $\delta^{13}C$ values (called the Suess effect [Kortzinger et al. 2003]). The actual decrease has been quantified as being between -0.024‰ (Kortzinger et al. 2003) and -0.026‰

(Quay et al. 2007) per year in the North Atlantic, which corresponds fairly well with the decrease in $\delta^{13}C$ in gannet eggs (-0.021‰). It is therefore possible that this decrease is largely attributable to the Suess effect. When $\delta^{13}C$ values are corrected to account for the Suess effect, the relationship is no longer significant. Some studies have also shown a decline in $\delta^{13}C$ values over several decades (Thompson et al. 1995; Becker and Beissinger 2006), while others have shown an increase (Hebert et al. 2008) or no change (Farmer and Leonard 2011). Hebert et al. (2008) attributed these changes to a change in the Herring Gull diet, which has shifted from pelagic prey (e.g., fish) to more terrestrial food resources (small mammals).

No change in trophic level as evidenced by $\delta^{15}N$ values was observed in the present study. Consequently, the decrease in contaminant concentrations over time in gannet eggs cannot be explained by a decrease in their trophic trophic level. A decline in trophic level has been observed in Great Black-backed Gulls on the coast of Nova Scotia (Farmer and Leonard 2011), as well as in Herring Gulls in the Great Lakes (Hebert et al. 2006; Hebert et al. 2008), in Marbled Murrelets (*Brachyramphus marmoratus*) in the Pacific Ocean (Becker and Beissinger 2006), and in Northern Fulmars in the northeast Atlantic (Thompson et al. 1995).

The accumulation of contaminants in Northern Gannets during the wintering period cannot be ruled out as a possible explanation for the observed concentrations (Lavoie et al. 2012). However, the Bonaventure Island colony was found to have higher organochlorine concentrations than a colony located at a considerable distance from major sources of contaminants (Funk Island, N.L., Elliott et al. 1988). Furthermore, stable isotope analysis has shown that, in the majority of aquatic bird species, most of the nutrients allocated to egg production are locally derived (Hobson et al. 1997; Hobson et al. 2000; Bond and Diamond 2010). The decline in concentrations of contaminants in gannet eggs at the Bonaventure Island colony therefore appears to reflect to a large degree a corresponding pattern of decrease in the species' food resources in the Gulf of St. Lawrence.

5 CONCLUSION AND RECOMMENDATIONS

The results presented in this report indicate that the Northern Gannet population in the Gulf of St. Lawrence is healthy. The two main gannet colonies showed steady growth over a 30-year period (1979–2009), thanks to the sustained high levels of breeding success, with the population nearly quadrupling in size. This indicates that the birds had access to abundant food resources in the Gulf of St. Lawrence and their reproduction was not affected by variations in the abundance of pelagic fish species such as mackerel, herring and Capelin, which are the main components of their diet. Breeding success was very good over this period, except in 2009, when it reached the lowest level seen since the 1970s. This finding, coupled with the worrisome outlook for stocks of some forage fish and changes in oceanographic conditions, which may be exacerbated by climate change, makes the future of Northern Gannets more uncertain.

Concentrations of most of the contaminants of concern in the eggs of this species were lower than those in the majority of waterbirds in Canada, North America and other countries, in spite of the Northern Gannet's high trophic level. Most of the contaminants show declining temporal trends, and contaminants that were historically considered a serious threat because of their toxicity (e.g., DDT) have fallen below toxic effect levels, resulting in a marked improvement in reproductive success and an increase in gannet numbers on Bonaventure Island. Although the levels of most contaminants have declined, the rate of decrease has slowed in recent years, and some studies suggest that these levels will continue to be detected in the future. It is too early to identify trends in brominated flame retardants in gannet eggs; however, if the trend reflected in the results for 2004 and 2009 is maintained, we can expect to see a decrease in the levels of these compounds over the coming years.

No temporal trends in stable carbon isotope values (corrected for the Suess effect) and stable nitrogen isotope values were identified in eggs at the Bonaventure Island colony. Consequently, it appears that trophic level and foraging area are not affecting the concentrations of contaminants found in gannets. Monitoring of the Northern Gannet diet should continue so the results can be compared with stable isotope trends.

Although most of the contaminants examined in this study show decreasing concentrations, new contaminants continue to be released through human activities. It is important to continue contaminant monitoring and to incorporate other, less-documented contaminants such as perfluorooctane sulfonate (PFOS), other perfluorinated compounds and polycyclic aromatic hydrocarbons into the monitoring program. The latter appear important with regard to potential future developments in the Gulf of

St. Lawrence and in light of the major oil spill that occurred in the Gulf of Mexico in 2010, which is where a significant proportion of the Northern Gannet population from Bonaventure Island spends the winter.

Monitoring of Northern Gannets has provided valuable information on the state of the Gulf of St. Lawrence for more than 40 years. It is important to continue the long-term monitoring of the Northern Gannet as a sentinel species of the state of the Gulf of St. Lawrence. Complementary studies could prove useful for gaining insight into the complex interactions between climatic variations (e.g., water temperature, extreme climatic conditions), the abundance and distribution of pelagic fish species, levels of contaminants, and their impacts on the Gulf of St. Lawrence ecosystem and the health of the Northern Gannet population in Quebec.

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8 APPENDICES

Appendix 1. Count of Northern Gannet nests on a digital photo.

In sectors occupied by the colony, breeding pair territories are spread very evenly, and density appears constant. Knowing that birds showing a less regular distribution and lower density in the periphery of the colony are non-breeders (e.g. bird on the right-hand side of the green line, on the photo), the latter are excluded from the colony count. Territories apparently occupied by breeding pairs are counted and marked with a red dot (see Appendix 2).

Appendix 2. Counting method using Adobe Photoshop version CS6.

1. Open the image file (*File → Open*). Select *Window→Navigator* to open the *Navigator* panel. The *Navigator* panel is useful to zoom in and out on the image.

2. Select *Window→Layers* to make the *Layers* panel appear. Create a layer over the photo (*Layer → New → Layer)* and name it.

3. Select the *Pencil tool* from the *Tools* panel.

4. Select a bright color that will stand out from the background image (e.g. : red). Click on the *Foreground color* box at the bottom of the *Tools* panel (left hand side of the screen), and the *Color picker* panel will appear. Select a bright red color, and take note of the numbers corresponding to this color (always use the same color). For example, choose R = 255, G = 0 and B = 0.

5. Define the size of the dots. Choose *Window→Brush* and the *Brush* panel will appear. Under *Brush Tip Shape*, check boxes *Shape Dynamics* and *Smoothing*.

   5.1 Select a solid, well-defined dot for the *brush tip* shape, and then select its *Size*, for example 5 px (see table 1 at the end of the appendix to see how many pixels there are per dot, depending on brush size). In the present example, a brush size of 5 px will draw dots composed of 21 pixels.

   5.2 Select maximum *Hardness* (100 %).

   5.3 Check the *Spacing* box and select maximum *Spacing* (1000 %). These last two operations are necessary to avoid overestimating the number of pixels per dot.

   5.4 Click **only once** on the (left) mouse button to make one dot on the layer over the image. This step is necessary to validate the number of pixels per dot, at the beginning. Otherwise, go to step 11.

6. In the *Layers* panel, click on the eye located to the left of the *Background* image ; this will hide the photo in the background and only the new layer on which the dots were drawn will appear. This step is optional, but it helps to see the dots you will select on step 7. Then, still in the *Layers* panel, select (click on) the layer on which one or more dots were drawn.

7. Select the dots you have drawn that you want to count : choose the *Rectangular Marquee* (dotted rectangle) in the *Tools* panel (left hand side of the screen) and trace a rectangle around these dots. Dragging the *Zoom slider* on the *Navigator* panel to zoom out allows to see the whole layer, if necessary.

8. Count the dots. To find how many pixels compose one dot, you can refer to table 1 below, and verify by selecting only one dot on step 7 and completing step 8. To count the dots, click on the *Histogram* tab on the upper right of the *Navigator* panel to view the *Histogram* panel. In the *Histogram* panel, choose the color of the *Channel* that corresponds to the color of the dots to be counted (ex: *Red*). Also in the *Histogram* panel, choose *Source = Selected layer*. In the histogram graph, place the cursor on the (vertical) bar that identifies the color of the dots (*Level* = 255 for pure red). Under the graph, verify that *Level* indicates 255 and that *Cache level* indicates 1. If the latter is not equal to 1 you will need to do an update by clicking the *Cache data warning icon* (triangle) that appears in the upper right corner of the histogram graph, otherwise the given *Count* value will not be valid. Once these steps are done, note the value for *Count* : it represents the total number of pixels of the chosen color, for the dots you selected. In this example, the *Count* value should be divisible by 21 (that is, the number of pixels per dot). So the value of *Count* divided by 21 gives the number of dots (marked nests) in the selected area.

N.B. The value of *Count* corresponds to the **total number of pixels**, so to get the number of nests you will have to divide the value of *Count* by the number of pixels per dot/nest, which depends on brush size (this concept is important to understand). For example, if you use a brush size of 10 px to draw the dots, you will have to divide the *Count* value in the *Histogram* panel by 80 to obtain the number of dots on the layer. The number of dots equals the number of marked nests.

9. Then, you have to cancel the selection tool used on step# 7. Choose *Select→Deselect*

10. Bring back the display of the background photo by clicking in the box located to the left of the *Background* image in the *Layers* panel (an eye will appear in the box).

Start to count

11. Select the layer created to count the nests (in the *Layers* panel) and, using the left mouse button, click (put a dot) on all the nests you wish to count on the image. Maximum *Spacing* set in the *Brush* panel (step 5.3) helps to prevent drawing a slightly blurred dot that would be composed of a larger number of pixels than a normal dot.

12. When all the nests are marked with dots, do again steps 6 to 10 but this time, select the whole layer with the *Rectangular Marquee* (step 7); then, when placing the cursor on the vertical bar (on the histogram) that corresponds to the color of the dots, the *Count* value represents the total number of pixels for **all** the dots made of this color (*Histogram* panel). You then have to divide the number of pixels by the number of pixels per dot (step 8 or Table 1). Make sure that the result is plausible*. For the first time, we recommend verifying several times during the count to make sure that you master the method.

*If, when dividing the total number of pixels (*Count* value) by the number of pixels per dot, the resulting number has decimals, there is a problem : for example, there could not be 12,7 dots (this result is not plausible).

13. Given that a single image can sometimes hold a large number of nests, it can be wise to count the dots and save the file a few times during the count. When the *Count* value is plausible, save the file and continue the counting. This will prevent starting all over again if, upon the next verification of the number of nests, the result is not plausible (result with decimals). In such case you can close the file without saving, and when you reopen it, you can continue the count after the preceding back-up.

Warning, very important! When starting the count with a given dot size, you must not change the brush size during the count, because in such case dividing the total number of pixels (*Count* value) by a number of pixels per dot (to obtain the number of nests) won't be possible.

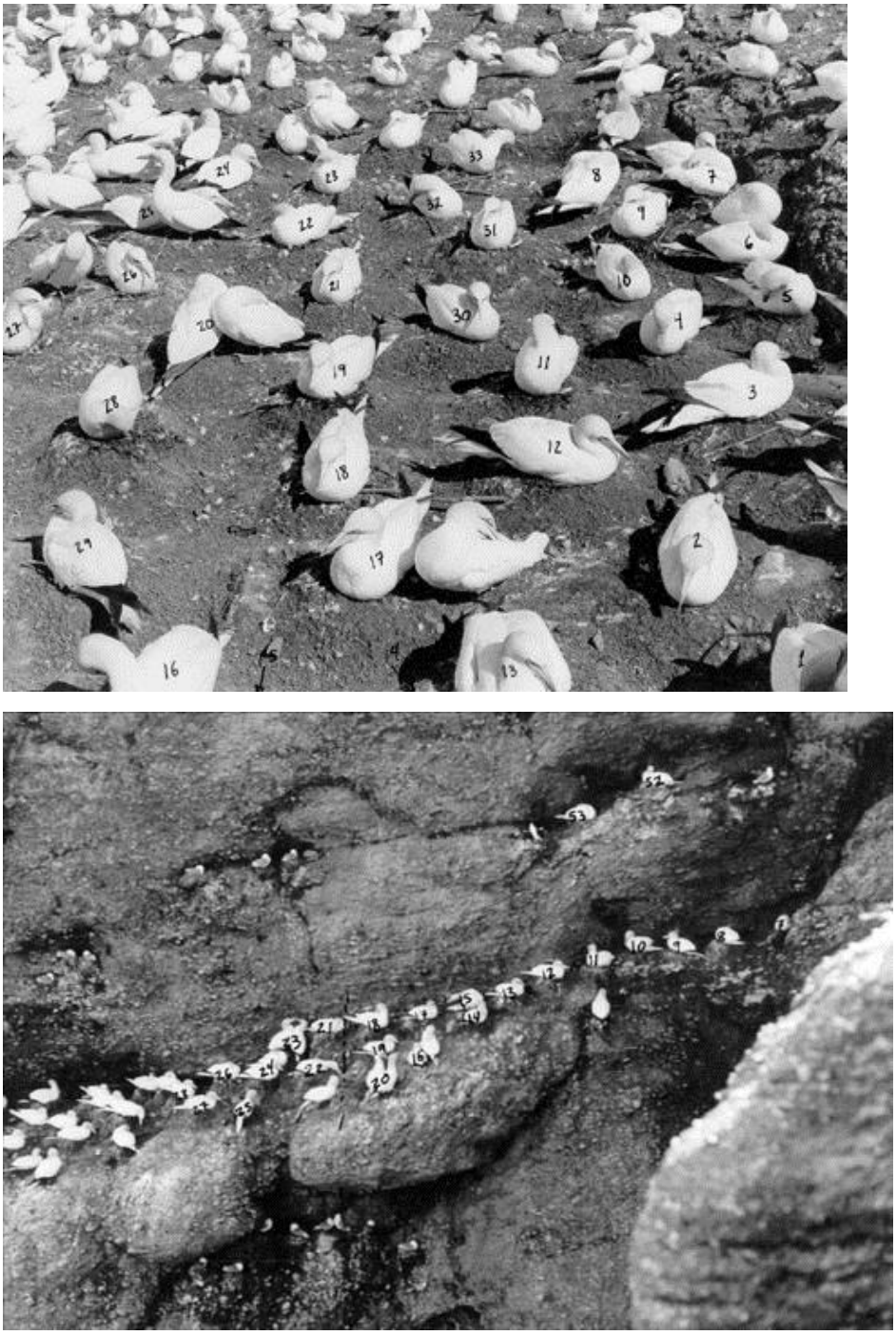
14. Enter in an Excel spreadsheet the number of nests (dots) for all processed images.

Table 1. Number of pixels per dot, corresponding to dot diameter

Brush size (pixels)	Number of pixels per dot
1	1
2	4
3	9
5	21
10	80
15	177

Appendix 3. Traditional method and set up used to count Northern Gannet nests on photos.

Here we see the counter-pointer device, the binocular magnifier, and the acetate sheet laid over the 20 × 25 cm enlargement of a photo showing part of the colony (here, Great Bird Rock).



Appendix 4. Illustration of the method used to monitor the nests of Northern Gannets on photo.

Groups of nests are photographed on the plateau (ex: top photo) and in the cliff (ex: bottom photo) from a precise location. Nests are then numbered on the photos, and several times during the season we go back at the exact place where a photo was taken to determine, using the picture to identify individual nests, the nest content of all numbered nests, in order to detail nesting success at every nest.

Appendix 5. Northern gannet feeding its young by regurgitation (top photo), and almost fresh mackerel regurgitated by a gannet (bottom photo).

Appendix 6. Diet of Northern Gannets at Bonaventure Island in 1995, 1999, 2003 and 2007.

Diet of Northern Gannets at Bonaventure Island, from 14 to 18 August 1995

Taxon n=80	Frequency of occurence	(%)	Numerical Frequency	(%)	Mass (g)	(%)
Atlantic mackerel	50	62.5	58	31.7	9285	67.1
Atlantic Herring	8	10.0	10	5.5	1411	10.2
Rainbow smelt	1	1.3	7	0.5	177	1.3
Sandlance *sp.*	4	5.0	92	50.3	570	4.1
Cunner*	1	1.3	1	0.5	144	1.0
Unidentified fish	19	23.8	21	11.5	2245	16.2
Total	-	-	183	100.0	13832	100.0

* *Tautogolabrus adspersus*

Diet of Northern Gannets at Bonaventure Island, on September 1st 1999

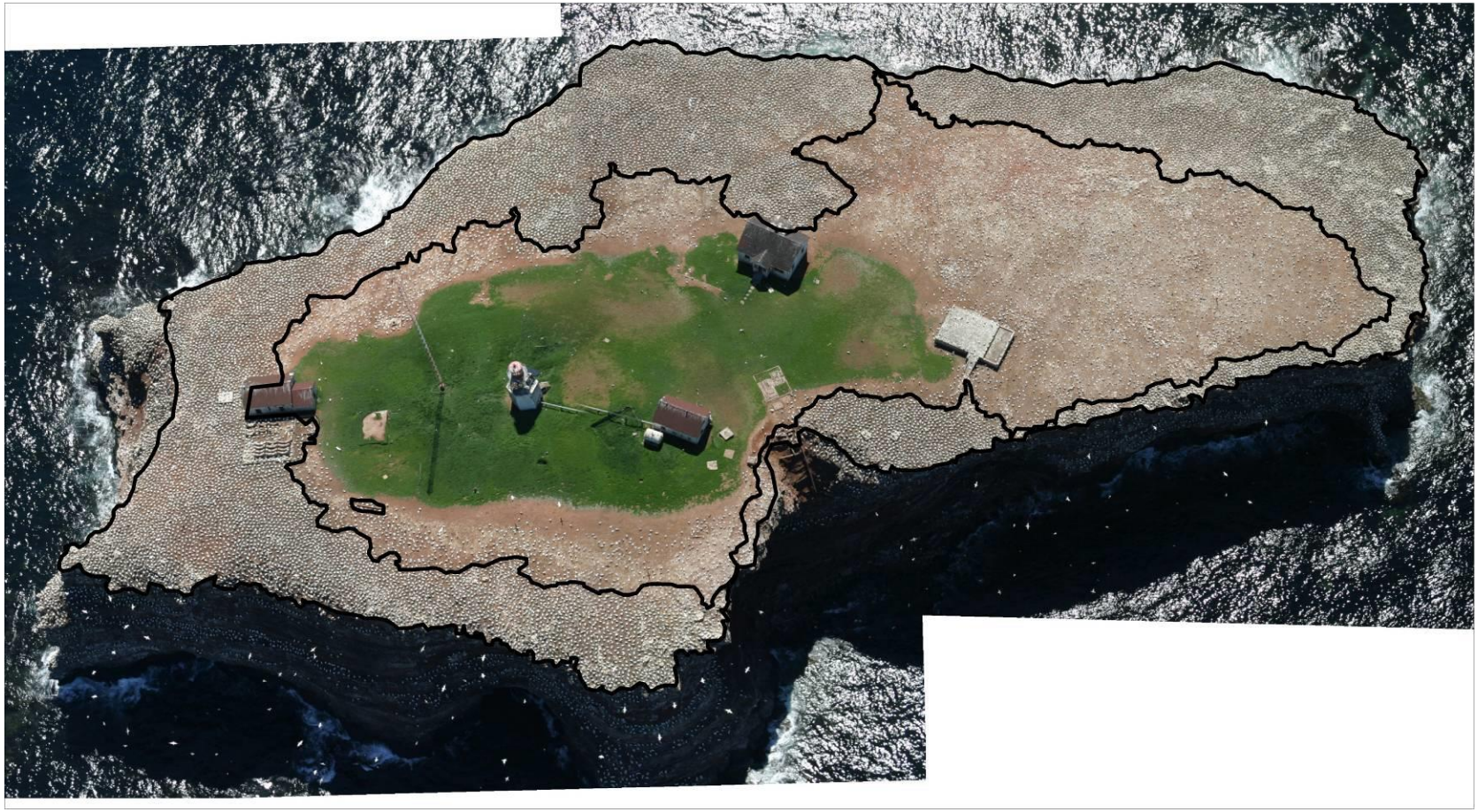
Taxon n=20	Frequency of occurence	(%)	Numerical Frequency	(%)	Mass (g)	(%)
Atlantic mackerel	3	15.0	3	12.0	287	8.3
Atlantic Herring	17	85.0	22	88.0	3172	91.7
Total	-	-	25	100.0	3459	100.0

Diet of Northern Gannets at Bonaventure Island, from 18 to 23 August 2003

Taxon n=30	Frequency of occurence	(%)	Numerical Frequency	(%)	Mass (g)	(%)
Atlantic mackerel	15	50.0	15	23.4	2023	56.4
Atlantic Herring	14	46.7	20	31.3	1266	35.3
Capelin	3	10.0	24	37.5	225	6.3
Sandlance *sp.*	2	6.7	3	4.7	7	0.2
Stickleback *sp.*	1	3.3	1	1.6	3	0.1
Squid *spp.*	1	3.3	1	1.6	65	1.8
Total	-	-	64	100.0	3589	100.0

Diet of Northern Gannets at Bonaventure Island, from 29 June to 2 July 2007

Taxon n=55	Frequency of occurence	(%)	Numerical Frequency	(%)	Mass (g)	(%)
Atlantic mackerel	47	85.5	64	70.3	5662.5	81.8
Atlantic Herring	10	18.2	13	14.3	1117.5	16.1
Capelin	2	3.6	10	11.0	117.5	1.7
Sandlance *sp.*	1	1.8	3	3.3	15.0	0.2
Rainbow smelt	1	1.8	1	1.1	10.0	0.1
Total	-	-	91	100.0	6922.5	100.0



Appendix 7. Nearly vertical view of the plateau of Great Bird Rock, Magdalen Islands, on 7 July 2004.

The area occupied by the Northern Gannet colony is delimited by the black line, and the estimated number of nests (or, of AOTs) on this area is 17,642 nests in 2004. The colony then occupied 42.26% of the total area of the plateau, and the unoccupied area (without taking into account the actual buildings) represents potential habitat for an additional 24,103 nests. Therefore, Bird Rocks can potentially hold approximately 48,000 Northern Gannet nests. More precisely, in 2004: 17,642 nests were counted on the plateau, plus 24,103 nests that could fill the available habitat towards the center of the plateau, plus 5,236 nests in the cliffs of Great Bird Rock and 583 nests on Little Bird Rocks, for a potential total of 47,564 Northern Gannet nests on Bird Rocks.

Appendix 8. Half-lifes (years) of PCBs and organochlorines in Northern Gannet eggs from Bonaventure Island and comparison with other studies.

	This report	**Elliott *et al.*** [1]	**Hebert *et al.*** [2]	**Alcock *et al.*** [3]	**Pereira *et al.*** [4]
PCB-118	10.7		5.7-3.4	5.9	5.0
PCB-138	12.4		5.7-4.7	7.5	3.2
PCB-153	17.3		7.7-6.2	10.1	18.0
PCB-180	16.5		6.5-6.2		
PCB-187	-		7.9--		
PCB-206	-		6.0-5.6		
1-ortho	10.8				
2-ortho	13.6				
3-ortho	23.9				
Tetra-PCB	8.6		4.1-2.2		
Penta-PCB	11.8		4.7-3.4		
Hexa-PCB	14.2		5.6-4.7		
Hepta-PCB	18.2		6.3-6.6		
ΣPCB_{38}	13.9				
Total PCB			5.6-4.3		
PCB 1:1	10.5	11.3			
α-HCH	21.0	-			
Total HCH	18.7	-			
pp'-DDT	4.3	3.9			
pp'-DDD	3.5	3.1			
pp'-DDE	5.7	3.6			
Total DDT	5.6				
t-nonachlor	8.8				
c-nonachlor	8.9	19.4			
Oxychlordane	14.8	35.4			
c-chlordane	8.3	11.2			
HE	15.4	-			
Total	12.2				
Dieldrin	9.5	7.4			
Mirex	13.6	-			
Total OC	6.7	-			

1: Elliott *et al.* 1988
2: Hebert *et al.* 1999b
3: Alcock *et al.* 2002
4: Pereira *et al.* 2009

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Additional information can be obtained at:

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