Effects of Bridge Construction and Wastewater Effluent on Phytoplankton Abundance and Sediment Geochemistry in an Atlantic Temperate Coastal Bay Since 1930

1 **Effects of bridge construction and wastewater effluent on phytoplankton abundance**
2 **and sediment geochemistry in an Atlantic temperate coastal bay since 1930**
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24

25 **Acknowledgement**

1 **Abstract**

2   Despite a recent proliferation of bridges in coastal zones, little is known of the

3 long-term impacts of bridge construction on phytoplankton abundance and community

4 composition in nearshore waters. Here, we used high performance liquid

5 chromatographic (HPLC) analysis to quantify historical changes in phytoplankton using

6 fossils from cores on either side of a 57-year old bridge that reduced fetch by 76% and

7 created a discrete enclosed inner embayment. We hypothesized that phytoplankton

8 abundance should be greater in the inner bay after bridge construction due to reduced

9 hydrological flow and increased nutrient influx associated with terrestrial development

10 and more profound anoxia in the enclosed basin. As expected, primary producer

11 abundance, especially cryptophytes, increased in the inner bay during the 1950-1960s,

12 although the effect was transient despite continuous four-fold elevation in sediment

13 organic matter content (%C, %N) after ca. 1960 in response to wastewater influx. The

14 pulse in cryptophytes appeared to correspond to influx of humic-rich waters derived from

15 locally-exploited peatlands, whereas the phytoplankton community of the outer basin

16 largely reflected historical variations in climate, with warmer April months associated

17 with increased abundance of diatoms and cryptophytes. Overall, sediment stable isotope

18 values in the inner basin varied in response to a complex combination of changes in

19 wastewater treatment (δ^{15}N), release of untreated fish plant effluents (δ^{15}N) and

20 connectivity with the open ocean (δ^{13}C). Taken together, these findings suggest that the

21 effects of bridge construction on coastal phytoplankton production and community

22 composition operated through multiple pathways, rather than just via modifications of

23 basin hydrology.

1 Introduction

2   Coastal zones support 33% of the global human population (Small and Nicholls

3 2003), a proportion which is expected to increase during the 21th century. Increasing

4 human settlement in coastal zones coincides with elevated phytoplankton abundances in

5 coastal waters, likely because terrestrial development has accelerated nutrient mass

6 transfer to nearshore waters following land clearance in the 19th century, municipal

7 wastewaters and other point sources during 1900-1950, and continued agricultural runoff

8 (Cloern 2001, Andersen and Conley 2009). Coastal human settlement has also been

9 accompanied by the construction of bridges and causeways designed to facilitate linear

10 vehicular transportation in a landscape dissected by bays and estuaries. For example,

11 there are more than 45 000 watercourse crossings in New Brunswick, Canada, a region

12 with only 0.75 million inhabitants (Jean-François Mallet, Canada Dept. Fisheries and

13 Oceans, pers. comm.).

14   In many cases, bridges are expected to modify hydrological flow regimes. When

15 water approaches a bridge, embankments redirect the flow towards the open water under

16 the bridge, resulting in increased upstream backpressure, but elevated current velocity

17 and water depth under the span due to scouring (Hamill 1999). In general, both current

18 and depth return gradually to natural values past the constriction. Flow modification due

19 to such basin closures usually occur in a region defined as approximately L/2 upstream to

20 Lx2 downstream, where L is the total length of embankments (Rene Garcia 2016). As a

21 result of these modifications, most modern bridge constructions require formal

22 environmental impact assessments prior to construction (Canadian Environmental

23 Assessment Act 2012). However, despite the well documented effects of bridges and

1 causeways on water flow, relatively little is known of their impacts on aquatic

2 ecosystems, particularly in comparison to full closure of flow by dams (Rosenberg et al.

3 1997, Li et al. 2013, Domingues et al. 2014). Like dams, bridges in coastal regions are

4 expected to reduce hydrological flow (Tas et al. 2009, Li et al. 2015), favour increased

5 sedimentation (Serieyssol et al. 2009), and favour elevated phytoplankton productivity or

6 abundance (Taylor et al. 2011, Paerl et al. 2014, Bowes et al. 2016, Brito et al. 2017).

7 Further, restriction of ocean inputs to inner bays can increase the local influence of land

8 on marine waters, including elevated depositions of terrestrial materials with unique

9 biogeochemical signatures such as C:N ratios (Sterner et al. 2008, Savage et al. 2010) and

10 carbon isotope ratio values (δ^{13}C) (Peterson and Fry 1987, Hoffman and Bronk 2006, Tue

11 et al. 2012, Vaalgamaa et al. 2013).

12   Here we perform the first quantitative test of the effects of embayment closure by

13 a bridge in production and biogeochemical features of a coastal straight environment.

14 Specifically, we compared fossil profiles of pigments from phytoplankton and stable

15 isotopes of C and N in sediment cores retrieved on either side of a 776-m long bridge

16 built in 1957-1959 that connects a 150-km^2 island to the mainland in Atlantic Canada.

17 We expected that sedimentation rates, fossil pigments, organic matter content, C:N ratio,

18 δ^{13}C and δ^{15}N should follow similar decadal patterns at the two coring sites until bridge

19 construction. Thereafter, we predicted that there would be a greater deposition of

20 sediments due to hydrological closure of the inner bay, resulting in elevated

21 phytoplankton abundance, changes in gross community composition and possibly

22 variation in C:N and δ^{13}C values reflecting change in the provenance of organic carbon.

23 Lastly, we hypothesized that the influence of climate variability on phytoplankton

1 abundance may be more pronounced in the outer basin than in the inner basin, due to

2 increased distance from land use changes (cf. Savage et al. 2002). Given the general lack

3 of environmental monitoring that followed the construction of many bridges in the 1950s,

4 we rely on a paleoecological approach to better assess the potential impacts of bridge

5 construction on algal abundance. To our knowledge, this is the first study that addresses

6 the long-term impact of bridge construction on algal community structure and water

7 geochemistry.

8

9 **Material and methods**

10 *Study area*

11   Shippagan Bay is located in the Acadian Peninsula of northeast New Brunswick,

12 Atlantic Canada (Fig. 1). This part of the Eastern Lowlands Ecoregion is characterized

13 by expansive bog peatlands (Zelazny 2007) where saltmarshes represent 8% of all habitat

14 types (Hanson and Calkins 1996). Shippagan municipality harbors 2,631 inhabitants

15 (Statistics Canada 2017), with a commercial port, a marina, an oyster farm, and the

16 Aquarium and Marine Centre of New Brunswick. Shippagan Bay is ~15 km long along

17 its north-south axis (Haigh et al. 2004) and 5 km wide (Duxfield et al., 2004) and can be

18 considered as a strait with a north to south orientation, separating Lamèque Island to the

19 east from the Shippagan mainland to the west (Fig. 1). The Bay communicates with the

20 Chaleur Bay to the north, the Saint-Simon Bay to the west, Lamèque Bay to the east, and

21 Shippagan harbor to the south. Shippagan Gully is located at the south-eastern limit and

22 has been heavily modified throughout the 20th century, especially during the 1960s-

1 1970s, to accommodate navigation between the Chaleur Bay to the northwest and the

2 Gulf of St. Lawrence to the southeast.

3　　　Local tidal cycles are lagged (Logan 2012, Haigh et al. 2004), with high tide

4 reaching the northwestern part of the Shippagan bay, ebbing from Chaleur Bay, some 20

5 minutes before reaching to southeastern part of Shippagan Bay (ebbing from the Gulf of

6 St. Lawrence, Dominique Bérubé, Geological Survey Branch, New Brunswick

7 Department of Energy and Resource Development, pers. comm. 2016-05-03). In contrast,

8 tide reversal at low tide occurs at the same time (Haigh et al. 2004). Ice sheets tend to

9 accumulate on the north-western side of the bridge in winter, suggesting currents are

10 overall stronger coming in from the north-western part of the Shippagan Bay than its

11 south-eastern part. Currents through Shippagan Gully, particularly during the ebb-tide,

12 have been observed to reach velocities of over 2 $m \cdot s^{-1}$, while the tidal range at the inlet is

13 generally on the order of 2 m or less (Logan, 2012).

14

15 *History of terrestrial and aquatic modifications*

16　　　Coastal waters near Shippagan have experienced diverse human interventions,

17 including water flow restriction (gully, bridge), nearby natural resource extraction,

18 treated municipal wastewater inflow, especially in the inner, southeast bay (Online

19 Resource 1). Historically, Mi'kmak First Nations occupied the Shippagan territory before

20 first European settlers established in the 18th century (Online Resource 1). The name

21 Shippagan itself originates from the Mi'kmak "Sepagun-chiche" ("Duck transit route").

22 In 1830, the William Fruing & Co started its fishing activities from the Shippagan harbor,

23 while the first dock was built in 1906 (Robichaud, 1976). Transportation by train to

1 Shippagan started 1887 and ended 1976. Industrial peat extraction commenced as early as

2 the 1940s within 1 km of the inner bay, while exploited surfaces expanded to ~ 120 ha on

3 the south shore and ~ 673 ha on the north shore (Online Resource 1). Peat extraction

4 involved soil drainage, vacuum extraction, but no use of fertilizer or pesticide. Cranberry

5 culture began in 1999 on 10 ha and reached 47 in 2016 (Fig. 1). During the 1880s, two

6 300 m jetties were constructed on either side of the gully inlet (Online Resource 1,

7 Logan, 2012). During 1965-1970, a 90 m-long jetty was added on the east side of the

8 gully (reducing inlet width), and a 600 m-long curved breakwater was built on the west

9 side.

10   Bridge construction took place 1957-1959 at the same location as prior ferry

11 operations. Prior to construction, the shore-to-shore fetch was ~ 776 long; however, the

12 200 m-long vertical-lift bridge (no pylons or piers) and over 800 m of causeway between

13 Lamèque Island and mainland reduced the fetch to 200 m, equivalent to a 76% reduction

14 in hydrological connectivity. Following bridge and causeway construction, the water

15 body east of the bridge is referred to as the "inner bay" (connected to the Gulf of St.

16 Lawrence via the gully), whereas the water body west of the bridge is the "outer bay"

17 (communicating with the Chaleur Bay ~ 10 km north).

18   During the 1950-1980s, up to five marine fish processing plants operated west of

19 the Shippagan port in the outer basin while a further two operated east of the bridge.

20 Operations gradually declined during the 1990s until the last fish plant closed in 2011.

21 Historically, waste and effluent from all plants were released into the bay with little or no

22 treatment.

1   Domestic houses and industrial operations also released wastes directly into the

2 bay until 1961 (Valmond Doiron, Shippagan City Engineer, pers. comm.). Following

3 that date, the municipality of Shippagan diverted the waters from over 1600 inhabitants

4 into an urban wastewater lagoon for secondary treatment to remove organic matter before

5 releasing effluents into the inner bay near Pointe-Sauvage (Fig. 1). A second lagoon was

6 built in 1978; however, treatment effectiveness varied thereafter due to treatment failures

7 in the early 1980s, addition of aerators in 1986, further failures in 1997-1998 and

8 installation of two new aerated lagoons in 2002. Thereafter, average effluent flow from

9 the wastewater treatment plant into Baie Sauvage ("inner bay") was 76 L·s^{-1} (14 to 153),

10 total phosphorus 1.1 mg·L^{-1} (0.2-2.9), nitrogen to phosphorus mass ratio 7.6. In 2012,

11 water temperature, salinity, turbidity, pH and dissolved organic carbon were comparable

12 between both stations, while total phosphorus and chlorophyll *a* were roughly two times

13 higher in the inner bay than in the outer bay (Online Resource 2). In short, the inner bay

14 experienced a greater diversity and intensity of human interventions compared to the

15 outer bay.

16

17 *Sampling*

18   Sediment cores were collected in 2012, from both the outer northwest basin (35

19 cm core at 47° 45′ 7.3″ N, 64° 41′ 57.5″ W) and inner southeast site (55 cm core at 47°

20 44′17.5″ N, 64° 41′ 23.5″ W) using a polycarbonate cylinder suction corer deployed in 1

21 m of water. Each core was extruded and immediately sectioned in 2-cm intervals under

22 subdued lighting. All the sediment samples were kept at -80°C until further analysis.

23

Laboratory Methods

Pigment analyses were performed using standard methods (Leavitt and Hodgson

2001) and fossil concentrations were expressed as nanomoles pigment g^{-1} organic matter

(nmol·g^{-1} OM). As lutein (chlorophytes) and zeaxanthin (cyanobacteria) co-elute on this

HPLC system, we report them as ''lutein–zeaxanthin'', an indicator of potentially bloom-

forming taxa. We computed the molar ratio of chlorophyll *a* to pheophytin *a* to assess the

changes in preservation of pigments in sediments (Reuss et al. 2005). Overall, nine

pigments were identified on the basis of chromatographic position and light absorbance

characteristics (350-750 nm) relative to authentic standards, and included β-carotene and

chlorophyll *a* (indicators of total biomass of primary producers), fucoxanthin and

diatoxanthin (mainly diatoms), echinenone (total cyanobacteria), canthaxanthin (colonial

cyanobacteria), chlorophyll *b* (chlorophytes), lutein-zeaxanthin (chlorophytes and total

cyanobacteria), and alloxanthin (cryptophytes). Taxonomic affiliations followed those

established by Leavitt and Hodgson (2001) and Paerl et al. (2003).

Lead-210 activities were measured at GEOTOP laboratories (Université du

Québec à Montreal). Measurements were based on alpha counting of the activity of ^{210}Po

($t_{1/2}$ = 138.4 days, alpha = 5.30 MeV), which is a daughter isotope of ^{210}Pb. Counting was

performed in a silicon surface barrier alpha spectrometer (EGG and ORTEC type 576A).

Chemical extraction, counting efficiency and estimation of uncertainties followed Not et

al. (2008). Counting uncertainty averaged 6% (range 4-8%), comparable to Turner et al.

(2006). Supported ^{210}Pb was estimated as the bottom three determinations of ^{210}Pb

activity (Binford 1990). The Constant Rate of Supply (CRS) model was chosen to

1 estimate sediment age because sedimentation rates are anticipated to have varied

2 throughout the 20th century.

3   Carbon and nitrogen isotope analyses were performed using a ThermoQuest (F-

4 MAT) Delta^{PLUS}XL isotope ratio mass spectrometer equipped with continuous flow (Con

5 Flo II) unit and an automated Carlo Erba elemental analyzer as an inlet device (Leavitt et

6 al. 2006). Stable nitrogen (N) and carbon (C) isotopic compositions ($\delta^{15}N$, $\delta^{13}C$) were

7 expressed in the conventional δ-notation in units of per mil (‰) deviation from

8 atmospheric N_2 and organic C standards previously calibrated against authentic Vienna

9 Pee Bee Belemnite. Sample reproducibility was ~0.11‰ and 0.10‰ for $\delta^{15}N$ and $\delta^{13}C$

10 determinations.

11

12 *Climate data*

13   Climate data (precipitation and air temperature) were downloaded from the

14 Government of Canada Climate Web site (http:// climate.weather.gc.ca/). Only two

15 climate stations in New Brunswick recorded daily data throughout most of the twentieth

16 century: Bathurst (station no 8100500) situated 75 km west of Shippagan, and Moncton

17 (station no 8103100) situated 185 km south. The Moncton data series was the longest and

18 most consistent climate data series and was shown to be an acceptable surrogate of

19 climatic conditions prevailing in the northeast of the province (Ady and Patoine 2016).

20

21 *Numerical analysis*

22   Principal component analysis (PCA) was used to represent temporal changes in

23 the pigment community and help identify periods of rapid change (Legendre and

1 Legendre 1998: 692). Redundancy analysis (RDA) was performed for each core with an

2 environmental data set comprised of 10 climatic variables (average monthly air

3 temperatures and precipitations for the months of April-August). Selection of

4 environmental variables followed Blanchet et al. (2008), using 1000 permutations.

5 Because the temporal resolution of climatic data (yearly) was finer than core age

6 estimates, we aggregated the climatic data into periods that matched the particular age

7 profile of each core (Table 1).

8   Graphics were generated with Tilia v.2.0.2 and Origin (v 6.1). Principal

9 component analysis (PCA) was performed with CANOCO v.5 (ter Braak and Šmilauer,

10 2002). Redundancy analysis (RDA) was performed in R version 3.1.1 (R Core Team

11 2014) with functions prcomp, rda, ordistep, forward.sel (Blanchet et al., 2008).

12

13 **Results**

14 *Sediment chronology*

15   The ^{210}Pb activity of the outer basin core declined continuously over the first 10

16 cm before reaching the background levels (Fig. 2a). In contrast, the ^{210}Pb activity profile

17 of the inner basin site was relatively constant over first 10 cm, followed by declining

18 activity to a baseline at 25 cm (Fig. 2b). Continuous Rate of Supply (CRS) calculations

19 suggested that both cores could be dated back to ca. 1935 CE (Figs. 2c, d, Table 1).

20 Extrapolation of sediment ages for the outer bay suggests that 9 cm depth represented ca.

21 1893 CE at that site.

22   In the outer bay, sedimentation rate for the entire dated period 1935-2012

23 averaged 1.6 mm·y^{-1} (±0.3 st. error); it increased to 1.8±0.2 mm·y^{-1}, for the period post

1 1957 (after the bridge construction). It was not possible to accurately estimate early

2 sedimentation rates before bridge construction in the outer bay because only one age

3 estimate was available prior to 1957. A similar increasing trend was noticed in the inner

4 bay where sedimentation values increased from 1.7±0.1 mm·y^{-1} (pre-1960) to 1.9±0.1

5 mm·y^{-1} (post-1957).

6

7 *Sediment geochemistry*

8   Average organic matter was relatively low (5%) and did not vary substantially

9 through time in the outer basin sediments (Fig. 3). While initially similar to the outer

10 basin (ca. 7%), organic matter content in the inner bay increased abruptly after ca. 1950

11 to 36% and remained higher than 20% thereafter (Fig. 4). Overall, C:N ratios were

12 slightly lower in the outer basin (11) than in the inner basin (13) (Fig. 5a), although,

13 temporal variability in C:N was generally high at both sites with few distinct trends

14 beyond a transient peak ca. 1990 in the inner basin.

15   Overall, $\delta^{13}C$ values were similar in both basin (~ -18-19‰), exhibiting only

16 minor (~2‰) variations through the past 100 years (Fig. 5b). The $\delta^{15}N$ values of the outer

17 basin sediments fluctuated within a narrow range (4.2 to 4.6‰) throughout the dated

18 interval of the core, whereas that of the inner basin decreased from >5 ‰ in the 1970s to

19 ~ 4.4 ‰ in the 2000s (Fig. 5c). Temporal variability of $\delta^{13}C$ and $\delta^{15}N$ was greater in the

20 inner bay than in the outer bay (Fig. 5d).

21

1 *Phytoplankton abundance*

2   Analysis of β-carotene concentrations from the outer-basin core suggests that total

3 phytoplankton abundances were generally greater during the 19th century than the 20th

4 century (Fig. 3). Similar declining trends were observed for pigments from cyanobacteria

5 (echinenone, lutein-zeaxanthin), especially colonial forms (canthaxantin), with the latter

6 not being detected after the 1890s. In contrast, alloxanthin (cryptophytes) and

7 diatoxanthin (diatoms) showed trends towards higher abundances after ca. 1950. Overall,

8 the chl *a* to pheophytin *a* ratio (indicating preservation environment) was stable and low

9 (0.3) prior to the 20th century, and doubled thereafter (Fig. 3), suggesting more favorable

10 preservation condition in recent times. In contrast, fucoxanthin and chl-a showed

11 exponential increases with time, a pattern that likely reflects the chemical instability of

12 these compounds relative to other biomarkers (reviewed in Leavitt and Hodgson 2001).

13 Unlike the outer basin core, concentration of most pigments in the inner basin tended to

14 peak in the 1950s-1960s, at 9-11 cm depths (Fig. 4) but otherwise showed little trend

15 beyond a secondary transient peak ca. 1988. This latter event also coincided with a brief

16 rise in the chl *a*:pheophytin *a* ratio indicative of better pigment preservation conditions.

17   Principal component analysis (PCA) of the outer basin site suggests a shift in

18 phytoplankton composition from a 19th century community with abundant cyanobacteria

19 (canthaxanthin, echinenone) to 20th century assemblage with more eukaryotes (Fig. 6a).

20 In contrast, the inner basin was characterized by periods of higher phytoplankton

21 abundance (years 1944, 1963, 1988, 2005 on axis I) alternating with periods of lesser

22 abundance (1978, 1998) (Fig. 6b). When data from both basins are co-ordinated in a

23 single PCA (Fig. 6c), inner basin phytoplankton community from 1944, 1963, 1988

1 formed a distinct cluster along PCA axis I, representing elevated abundance of

2 chlorophytes (chl-b) and cryptophytes (alloxanthin).

3   Redundancy analyses of the outer basin data showed that greater concentrations of

4 the carotenoids diatoxanthin (diatoms) and alloxanthin (cryptophytes) were associated

5 with higher April temperatures after the 1980s (Fig. 7, % inertia explained=62%,

6 p=0.04). In contrast, none of the 10 climatic variables were significant ($p > 0.05$)

7 predictors of changes in fossil pigment assemblages in the inner core.

8

9 **Discussion**

10   Despite close spatial proximity of both coring sites (1.7 km), sediment cores

11 revealed different patterns of decadal variations of pigment concentration and

12 biogeochemistry, corresponding to variations in infrastructure development, basin-

13 specific hydrology, and land use. For example, the inner basin core showed greater $\delta^{13}C$

14 and $\delta^{15}N$ temporal variability (Fig. 5d) in response to adjacent coastal development,

15 whereas pigment assemblages in the outer basin appeared to respond mostly to changes

16 in climate (Fig. 7). Overall, patterns of variation did not support the central hypothesis

17 that bridge construction resulted in a major change in basin hydrology, or phytoplankton

18 abundance (Figs. 3, 4) despite concomitant changes in sediment geochemistry.

19   Studies that have examined the spatial variability of stratigraphies among cores

20 extracted from a single coastal water body tend to show that among-core variability is

21 low relative to within-core (temporal) variability when cores are collected a few meters

22 apart (Chen et al. 2001) or at distances of 1 km (Cooper 1995) and up to 10 km (Savage

23 2005, Turner et al. 2006), particularly in the absence of strong riverine influence (see

1 Petersen et al. 2003). Instead, given the absence of large freshwater inflows, differences

2 among cores in the same coastal water body reveal the unique patterns of landuse and

3 climate at distances of 20-30 km (Andrén 1999, Li et. al. 2011). Consequently, given that

4 our cores are each < 1 km from the bridge (total 1.7 km apart), we presume that

5 differences in sites reflect mainly the effects of major disruption to hydrology or

6 geochemistry arising in part from bridge construction, although we recognize that further

7 research will be required at other bridges to confirm our novel findings (see below).

8

9 *Effects of basin development on sediment geochemistry*

10 Sedimentation rates estimated herein (0.9-2.2 mm/y) are similar to those reported

11 for other estuarine or coastal environments (Chen et al. 2001, Turner et al. 2006, Li et al.

12 2011, Ady and Patoine 2016). As expected, we observed slightly higher sedimentation

13 rates in the inner bay than in the outer bay, likely reflecting both reduced flushing of

14 particulate matter to the open ocean following the 1957-1959 bridge construction and

15 increased resuspension of local materials due to dredging and modification of the gully

16 during the 1960s and 1970s. Onset of industrial peat extraction on both sides of the inner

17 bay (Fig. 1) as early as the 1940s (Online Resource 1) could also have contributed to

18 increase the particulate mass influx to the inner bay, due to increased soil erosion and loss

19 to adjacent surface waters (Clément et al. 2009). Finally, transient increases in

20 phytoplankton abundance (Fig. 4, see below) within the inner site may have favored

21 increased sediment deposition.

22 Bridge construction altered the deposition of organic matter in the inner basin

23 (Fig. 4). Specifically, organic matter content increased permanently after bridge

1 construction in the 1950s, but was unchanged in the outer bay. While the organic content

2 values of 4-7% observed in the outer bay are comparable to those reported for

3 subtropical, agricultural-dominated coastal watershed estuaries in Florida (Turner et al.

4 2006) and eastern Australia (Logan et al. 2011), those for the inner bay post-1959 were

5 roughly double values typical of nearshore waters, reaching 20-36% (Fig. 4). Although

6 mechanisms are difficult to fully confirm, these changes likely arose because of the

7 combined effect of wave erosion of excavated peatlands (Zelazny, 2007), long-term

8 changes in wastewater inputs (Online Resource 1), and elevated primary production (Fig

9 4). Such a two-fold increase of organic matter content is similar to that observed in other

10 coastal waters experiencing wastewater inputs, such as New Bedford Harbour (Chmura et

11 al. 2004).

12   Throughout the outer bay core, the C:N ratios (10-12) of whole sediments

13 reflected the importance of coastal algae (<8, Kendall et al. 2001, Ock and Takemon

14 2014) and carbonate deposition (Gattuso et al. 1998, Savage et al. 2010). In the inner

15 bay, the lowest values (~12) were observed about the same time as the bridge

16 construction and the algal peak, supporting the idea that the C:N ratio might reflect the

17 importance of algal biomass to particulate matter. The C:N peak of 15 observed ca. 1990

18 in the inner basin could reflect an increased contribution from inorganic sediments

19 following the 1989 and 1993 channel dredging (Online Resource 1).

20   Sediment $\delta^{13}C$ values recorded herein (-20 to -18‰) were higher than those

21 reported in previous paleoecological studies (-32 to -20‰) set in coastal or estuarine

22 environments (Turner et al. 2006, Savage et al. 2010, Jin et al. 2010, Logan et al. 2011).

23 The extensive saltmarshes and eelgrass beds that characterize the Shippagan region to

1 this day (Hanson and Calkins 1996) may explain the exceptionally enriched ^{13}C signal

2 observed throughout the core, as seagrasses are known to undergo little carbon

3 fractionation relative to typical C3 terrestrial plants, despite their common use of ribulose

4 1,5-bisphosphate (RuBP) carboxylase to fix CO_2 (Benedict et al., 1980). Sedimentary

5 $\delta^{13}C$ values as high as -20 to -18‰ have also been reported for eastern north America,

6 but only prior to intensified coastal development (19th century, Chmura et al. 2004).

7 Hence, the continued importance of eelgrass in Shippagan Bay may explain the elevated

8 $\delta^{13}C$ signal.

9   The $\delta^{13}C$ temporal variability was as great on both side of the bridge (Fig. 5b),

10 such that it is difficult to interpret peaks and troughs as the result of human-made

11 modification to the gully. However, slightly higher (~ 1‰) $\delta^{13}C$ values in the inner bay

12 core sediments relative to those from the outer bay are consistent with the inner bay

13 core's greater proximity to open oceanic waters (3 km to the gully) relative to that of the

14 outer bay core (10 km to the Chaleur Bay). Indeed, the $\delta^{13}C$ signature of sediments

15 typically increases in coastal zones as one moves closer to the open ocean, where the

16 importance of atmospherically-derived dissolved inorganic carbon increases ($\delta^{13}C$ ~

17 0‰), to the detriment of CO_2 derived from respiratory processes (Martineau et al. 2004,

18 Turner et al. 2006, Hoffman and Bronk 2006, Vaalgamaa et al. 2013, Kaiser et al. 2014).

19 Hence, the $\delta^{13}C$ separation between inner and outer bay may reflect proximity to oceanic

20 inorganic carbon sources.

21   In both cores, maximum $\delta^{15}N$ values were reached during the 1950s-1960s,

22 coincident with the inner bay wastewater treatment plant startup and the period of peak

23 activity of the outer bay fish plants (Online Resource 1). Indeed, coastal sites receiving

1 treated wastewaters (Savage et al. 2010) or fish farming effluents (Vaalgamaa et al. 2013)

2 usually display a slightly higher $\delta^{15}N$ signature relative to reference sites. These results

3 are also consistent with high N-loading figures from seafood processing plants in the

4 Shippagan-Lamèque area (McIver et al. 2015). The important post-1970 $\delta^{15}N$ decline in

5 the inner bay could be the result of the municipal sewer pipe network becoming

6 increasingly leaky (accounting for the high effluent flow of 76 L·s^{-1} in the 2000s, Online

7 Resource 1), with increasing amounts of groundwater seeping into the system, diluting

8 the wastewater and giving the final effluent a low $\delta^{15}N$ signature, typical of groundwater

9 set in undeveloped areas (Komor and Anderson 1993). The post-1970 $\delta^{15}N$ decline

10 observed in the outer bay is consistent with the gradual shutdown of fish plants during the

11 1990s.

12

13 *Effects of basin development on algal assemblages*

14   The range of pigment concentration reported herein (10-500 nmol/g OM) was

15 comparable to that reported for other coastal zones (Chen et al. 2001; Bianchi et al. 2002;

16 Reuss et al. 2005; Savage et al. 2010; Ady and Patoine 2016). Similarly, ratios of labile

17 precursor-stable product compounds (Chl *a* : pheophytin *a*) observed here (0.2-2.2) were

18 comparable to those reported in other estuarine studies (Reuss et al. 2005; Savage et al.

19 2010) and suggested few changes which would obscure interpretation of the fossil

20 pigment record. Consequently, the observation that algal abundance in the inner bay

21 increased only briefly after bridge construction (Fig. 4) suggested that, contrary to

22 expectations, there was no sustained increase in algal abundance as result of hydrologic

23 closure of the inner embayment. Although fossil pigment concentration exhibited a

1 secondary peak in the late 1980s, this event coincides with similar variations in sediment

2 preservation (as chl *a*:pheophytin ratio), suggesting a sudden but transient improvement

3 in pigment preservation conditions.

4   Overall, algal abundance varied only modestly, despite changes in water

5 circulation (bridge construction, gully maintenance), nutrient pollution (treated sewage

6 inputs) and land use practices (peat extraction). Similar to Brito et al. (2017), we found

7 that bridge construction was associated with increased algal biomass, an effect the

8 authors attribute to the decreased flow and increased nutrient accumulation on the

9 landward side of the bridge. However, in our case, the effect was mild and short-lived

10 (1950s-1960s), possibly because both sides of the bridge remain connected to oceanic

11 water masses (Chaleur Bay to the northwest, Gulf of St. Lawrence to the southeast) and

12 there were few significant sources of freshwater to the inner basin (cf. Ady and Patoine

13 2016, Petersen et al. 2003). Although speculative, we suggest that limited algal response

14 may demonstrate that some level of water replenishment from the ocean may have been

15 maintained, despite restriction following the bridge construction.

16   Several paleooceanographic studies of estuarine environments report increased

17 diatom biomass following wastewater inputs (Savage et al. 2010 and references therein).

18 In contrast, we report episodic increases of chlorophytes and cryptophytes post-1959 in

19 the inner bay (Figs. 4, 6b). Although speculative, we feel that the rise in these groups,

20 normally a minor component of marine phytoplankton assemblages (Borges Mendes et

21 al. 2017), may mainly reflect changes in the influx of highly colored humic substances,

22 compounds which favor cryptophytes in both lakes (Jones 2000, Klug 2002, Waters et al.

23 2012) and coastal settings (Kimmerer et al. 2012). Here, the extensive peat extraction

1 activities that started in the 1940s-1950s on both terrestrial sides of the inner bay (Online

2 Resource 1) could have contributed to humic substances export to the inner bay (Surette

3 et al. 2002) and favored mixotrophic production in response to change in organic matter

4 characteristics.

5   Overall, if bridge construction favored algal abundance through reduced

6 hydrodynamics, it only did so transiently during the 1960s. Instead, modification to the

7 gully during the 1960s and 1970s could have shifted the hydrodynamic regime to yet

8 another state, not as favorable to algal growth, accounting for declining algal levels in

9 more recent times (except for chlorophytes and cryptophytes).

10   Bridges spanning coastal bays and estuaries are common in Atlantic Canada. For

11 example, there are at least 96 bridges across 30 estuaries within a 50 km by 200 km

12 region from Shippagan south to Shediac, New Brunswick. These bridges span river

13 widths varying from 25 to 850 m (median 100 m, inter-quartile range 70-230 m).

14 Although less common than spans over estuaries, bridges also overpass straits in the

15 regional coastline, with 11 spans over straits within three Canadian Atlantic provinces.

16 These strait bridges cross 80 m to 12 900 m of water (inter-quartile range 267 to 1313 m),

17 including the Shippagan bridge (776 m of natural fetch). Nine of these strait bridges

18 connect mainland to islands each with unique degrees of residential, commercial or

19 industrial development. Future studies should compare historical changes in marine

20 production to estimate the regional impacts of continued human population growth and

21 bridge construction. Based in this study, we anticipate that impacts may only be evident

22 when strait bridges restrict circulation more than 75%, or less for bridges spanning bays

23 or estuaries (cf. Brito et al. 2017).

1

2 *Effects of climate on coastal production*

3   April temperature was a significant predictor of changes in fossil pigment

4 assemblages, but only in the outer basin site (p=0.04, Fig. 7). The positive effect of

5 increasing temperature on phytoplankton biomass has already been reported for other

6 coastal systems (e.g., Rodrigues and Pardal 2015), although factors related to land-use

7 can dominate over climatic effects. Indeed, Savage et al. (2010) show that, while climatic

8 variables (including annual total precipitation, annual average temperature) become more

9 important correlates of estuarine phytoplankton community composition in recent years

10 (1975-2000) relative to prior periods (1950-2000, 1880-2000), land-use factors

11 (agriculture and wastewater treatment plant activities) remain stronger drivers at all time-

12 scales examined. Similarly, we could detect the influence of warmer spring seasons on

13 phytoplankton biomass (Fig. 7), but only at the site less impacted by land activities (outer

14 bay), suggesting that climatic effects on biota is easily overshadowed by local alterations

15 of the physical environment (Savage et al. 2002).

16   The shift from cyanobacteria to eukaryotes with warmer spring temperature in the

17 outer bay (Fig. 7) is contrary to expectations based on laboratory experiments showing

18 that cyanobacteria have a higher temperature growth optimum than eukaryotic groups of

19 algae and should thus be favored in warmer environments (Paerl et al. 2014). While some

20 field studies do confirm the prevalence of cyanobacteria in warmer waters (Paerl et al.

21 2011, Carstensen et al. 2015), it is not universal (Phlips et al. 2010) and also depends on

22 hydrological features, nutrient ratios, and irradiance regimes (Kahru et al. 1994; Paerl et

23 al. 2011).

1

Conclusions

2

3   Here we show for the first time that bridge and causeway constructions produced

4 few sustained changes in algal abundance or composition at the scale of decades (Figs. 4,

5 8). Instead, it appears that sewage input to the inner bay likely had a paramount effect on

6 water chemistry and biology as evidenced by the sharp decline in sedimentary $\delta^{15}N$ after

7 initial wastewater treatment plant influx and by the sustained increase in organic content

8 of sediments. In contrast, variations in algal abundance in the outer bay, where human

9 perturbations were less likely to be propagated, were better associated with historical

10 variations in climate, specifically temperature.

11   Based on this study, we predict that bridge constructions will have mild impacts

12 on phytoplankton assemblages wherever both sides of the bridge maintain a hydrological

13 connexion to marine water masses, but that damages could occur when infrastructure

14 inhibits oceanic exchange by closing more than 75% of the embayment mouth. Given

15 the dearth of similar studies on bridge impacts (e.g., Brito et al. 2017), we suggest that

16 future work should quantify how the magnitude of effects on primary production may

17 vary with the degree of flow restriction.

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5

1 **Table 1** Continuous rate of supply (CRS)-estimated age according to the mid-point of the

2 sediment intervals with lower and upper limit of the defined time period used to

3 aggregate yearly meteorological data

Site	Sediment interval (cm)	Mid-point	Lower year limit for data aggregation	Upper limit	Time period	Estimated year, based on CRS model (CE)
Shippagan northwest ("outer")	0-2	1	2001	2012	P4	2007
	2-4	3	1985	2000	P3	1996
	4-6	5	1955	1984	P2	1975
	6-8	7	1916	1954	P1	1935
	8-10	9				1893 extrap.
Shippagan east ("inner")	0-2	1	2002	2012	P7	2005
	2-4	3	1993	2001	P6	1998
	4-6	5	1983	1992	P5	1988
	6-8	7	1970	1982	P4	1978
	8-10	9	1953	1969	P3	1963
	10-12	11	1940	1952	P2	1944
	12-14	13	1932	1939	P1	1936

4

1 **Figure captions**

2 **Fig. 1** Map of Shippagan area showing the 1959 bridge that divided the bay in an outer

3   bay (northwest) and an inner bay (southeast), the two coring sites (full dots), the port

4   (circle), the municipal effluent discharge point (star) and roads (lines)

5 **Fig. 2** Vertical profiles of ^{210}Pb activity (left column) and Continuous Rate of Supply

6   model ages (right column) for the outer bay (top row) and inner bay (bottom row)

7 **Fig. 3** Algal pigment concentration vertical profiles in the outer bay along depth (cm) on

8   the primary axis and CRS-derived years on the secondary axis. Pigments includes: β-

9   carotene, chlorophyll *a* (all plants), fucoxanthin, diatoxanthin (diatoms), echinenone,

10   lutein-zeaxanthin, canthaxanthin (cyanobacteria), chlorophyll *b* (Plantae, Chlorophyta,

11   Eugluenophyta) and alloxanthin (cryptophytes). Also shown are the chlorophyll *a* to

12   pheophytin *a* ratio (an index of preservation), and sediment organic content (% of dry

13   mass)

14 **Fig. 4** Same as Fig. 3, but for the inner bay

15 **Fig. 5** Vertical age profiles of sedimentary (a) C:N ratio (b) δ^{13}C, (c) δ^{15}N, (d) for

16   Shippagan northwest "outer bay" (dashed-line with black upright triangle) and

17   southeast "inner bay" (solid-line with black inverted triangle) (d) Biplot of δ^{13}C and

18   δ^{15}N shows how outer bay samples (triangles) cluster apart from inner bay samples

19   (squares connected through time)

20

1 **Fig. 6** Principal component analysis biplot of outer bay (a), inner bay (b), and pooled (c)

2   core pigment community composition, with pigment as "species" vectors, and depths

3   (cm) as objects; CRS-estimated years for topmost depths (1-9 cm) are also indicated.

4   Sib: Shippagan "inner" bay (1944, 1963, 1988 surrounded by dashed line); Sob:

5   Shippagan "outer" bay

6 **Fig. 7** Redundancy analysis of the outer bay fossil pigment community as a function of

7   April air temperature; fraction of inertia explained by the single canonical axis: 62%

8   (p=0.04)

9 **Fig. 8** Conceptual diagram showing how documented historical events (dashed-outline

10   boxes) may have influenced observed trends in phytoplankton abundance and

11   geochemical indicators (bold-outline boxes) via presumed modifications in water flow

12   and color (plain boxes)

13

1 **Online Resource 1** Timeline of selected events that potentially influenced the ecology of

2 Shippagan Bay or that characterized Shippagan's urban and industrial development.

3 Information relating to boardwalk construction and wastewaters is from Valmond

4 Doiron, Shippagan Municipal Engineer (pers. comm. 2016-06-29, 2017-01-12).

5 Population numbers were compiled from Statistics Canada. Other sources are indicated,

6 or from Robichaud (1976), Mallet (2012)

7

8 **Online Resource 2** Sub-surface water quality at coring sites on coring date August 1st,
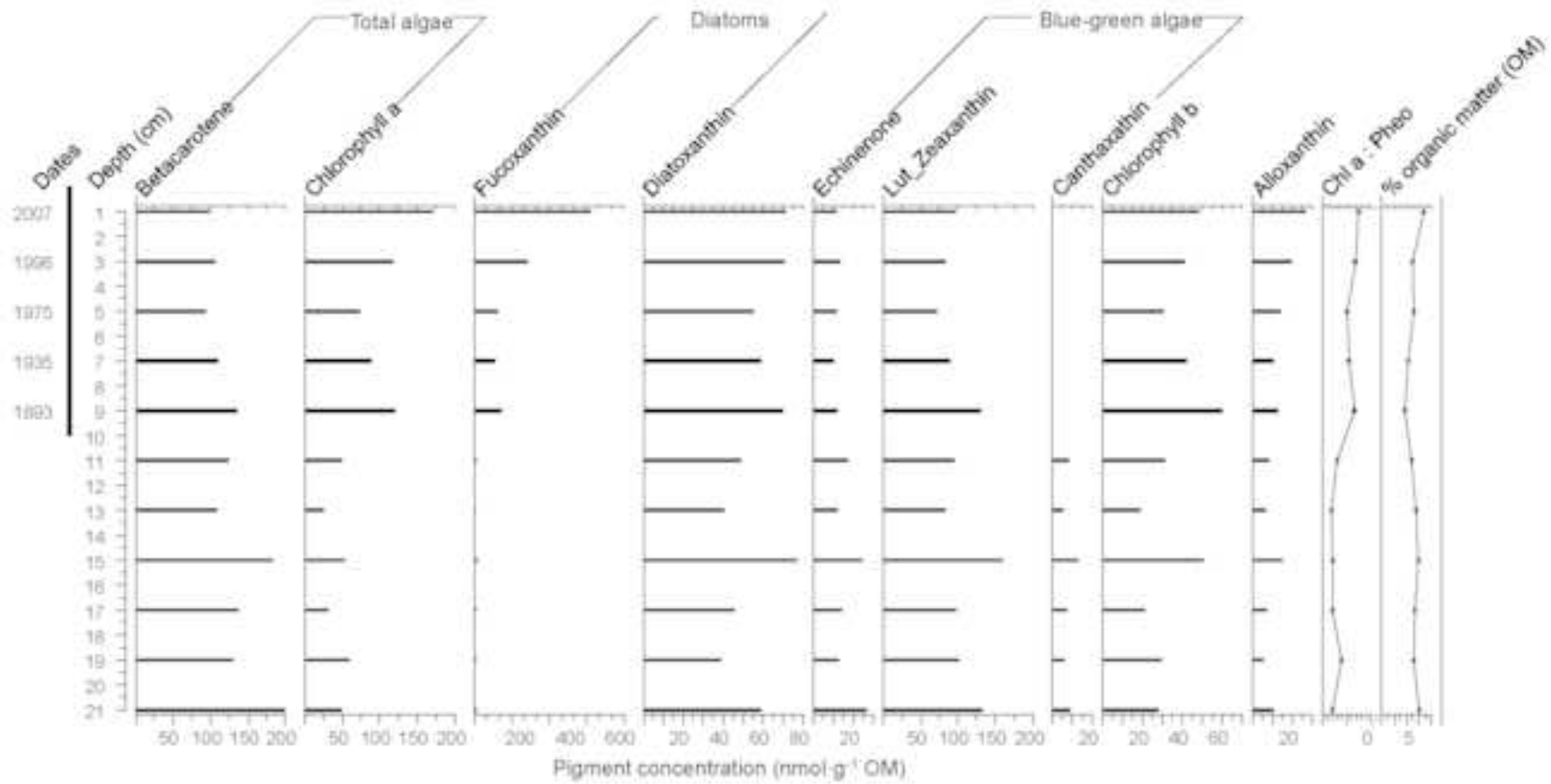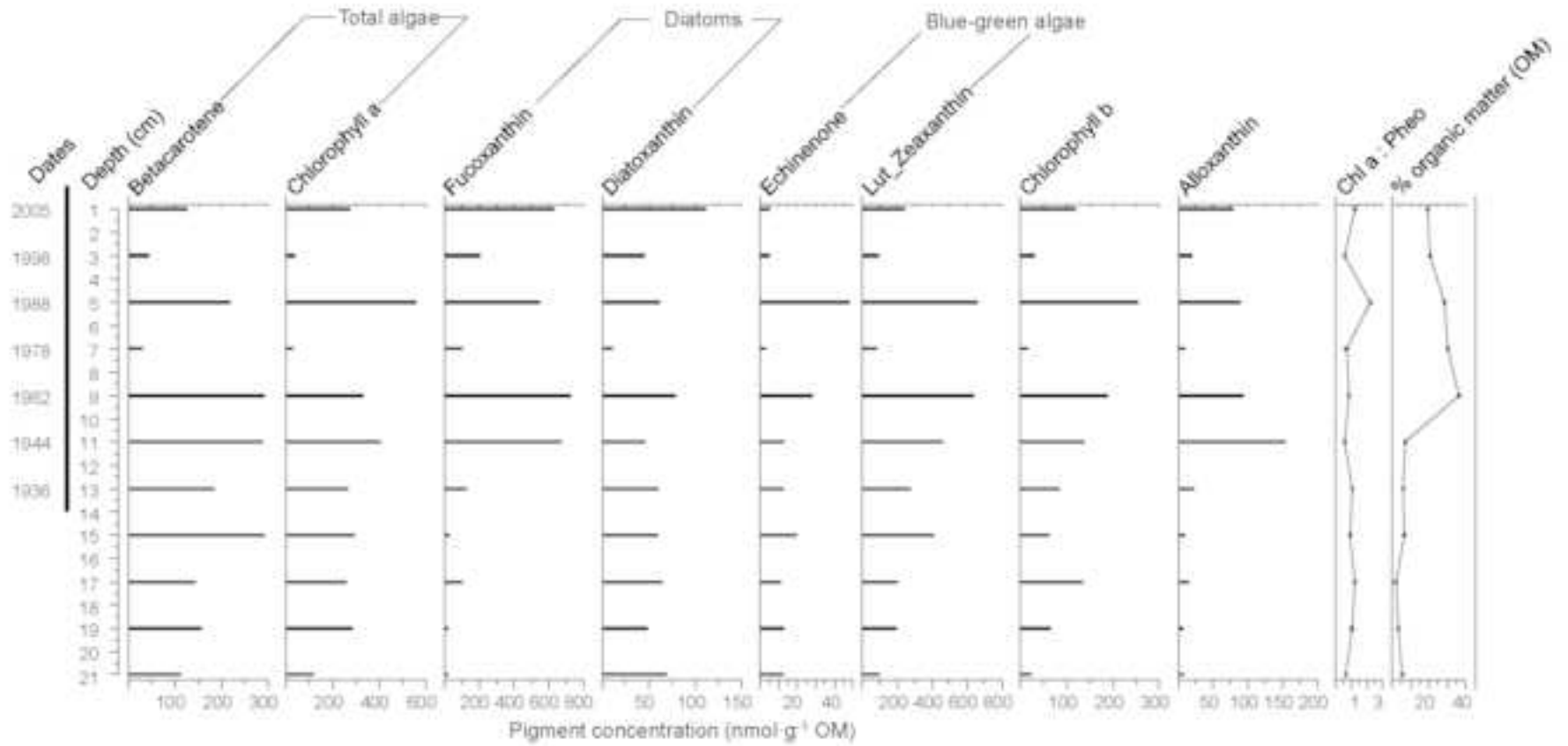
9   2012

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

a) Shippagan outer bay

b) Shippagan inner bay
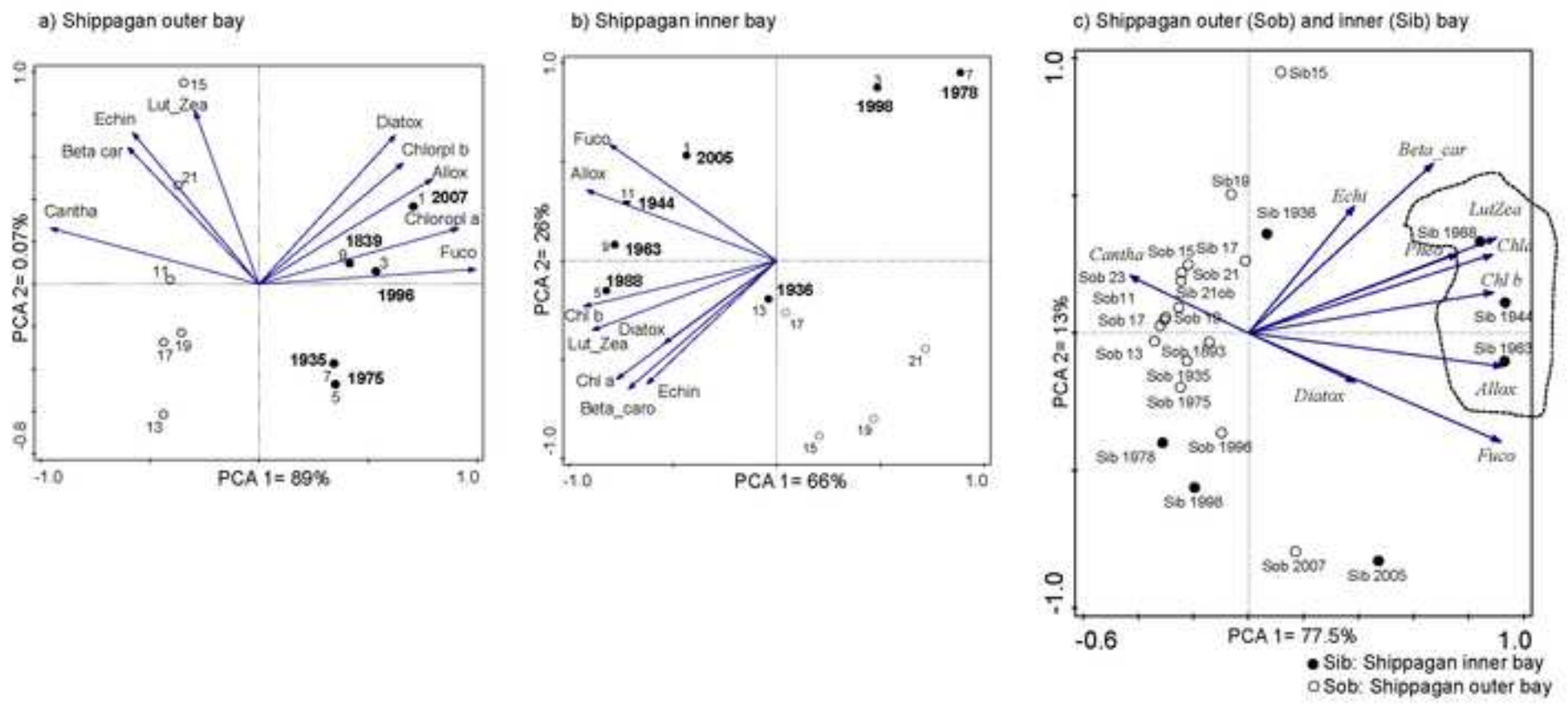
c) Shippagan outer (Sob) and inner (Sib) bay
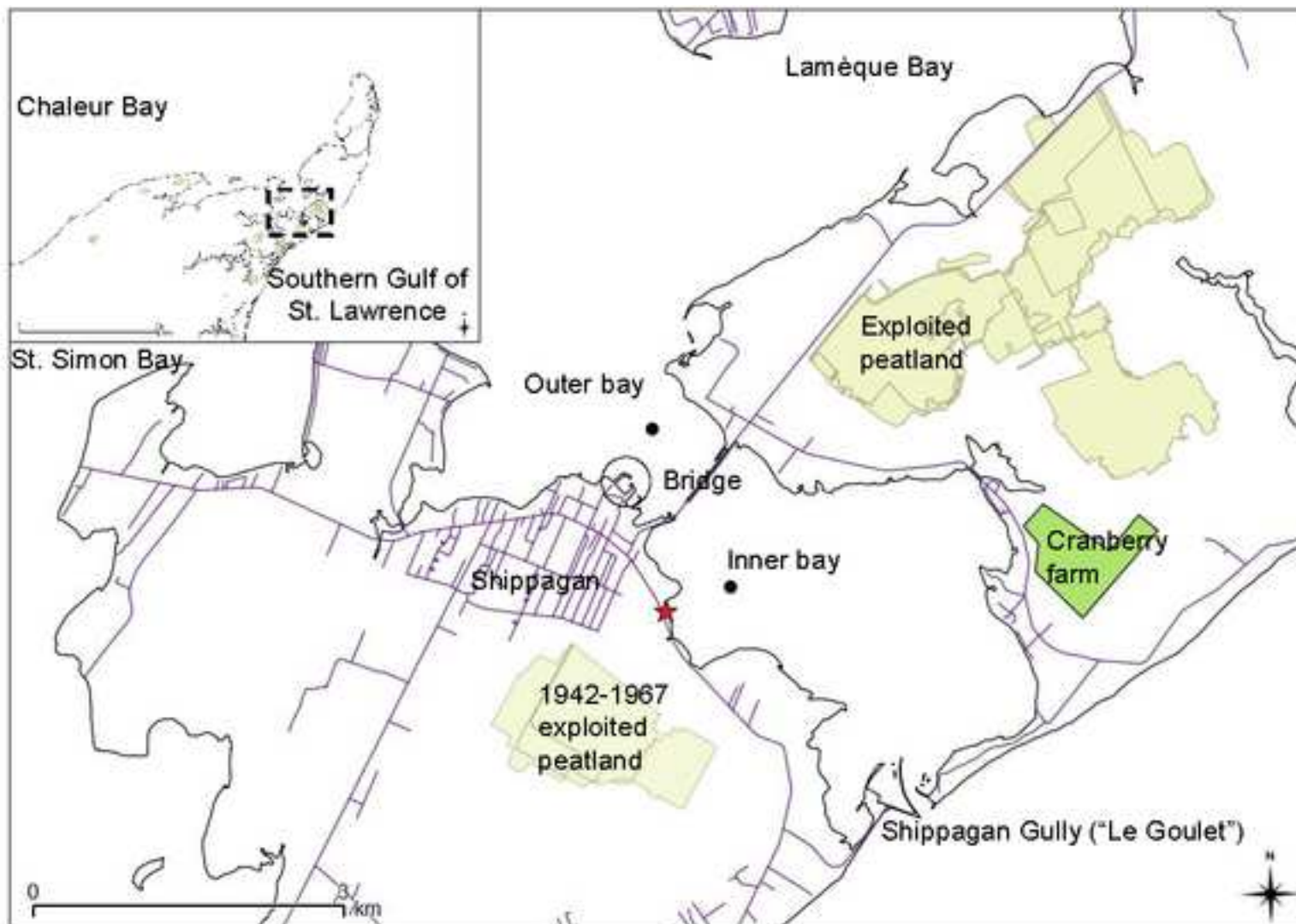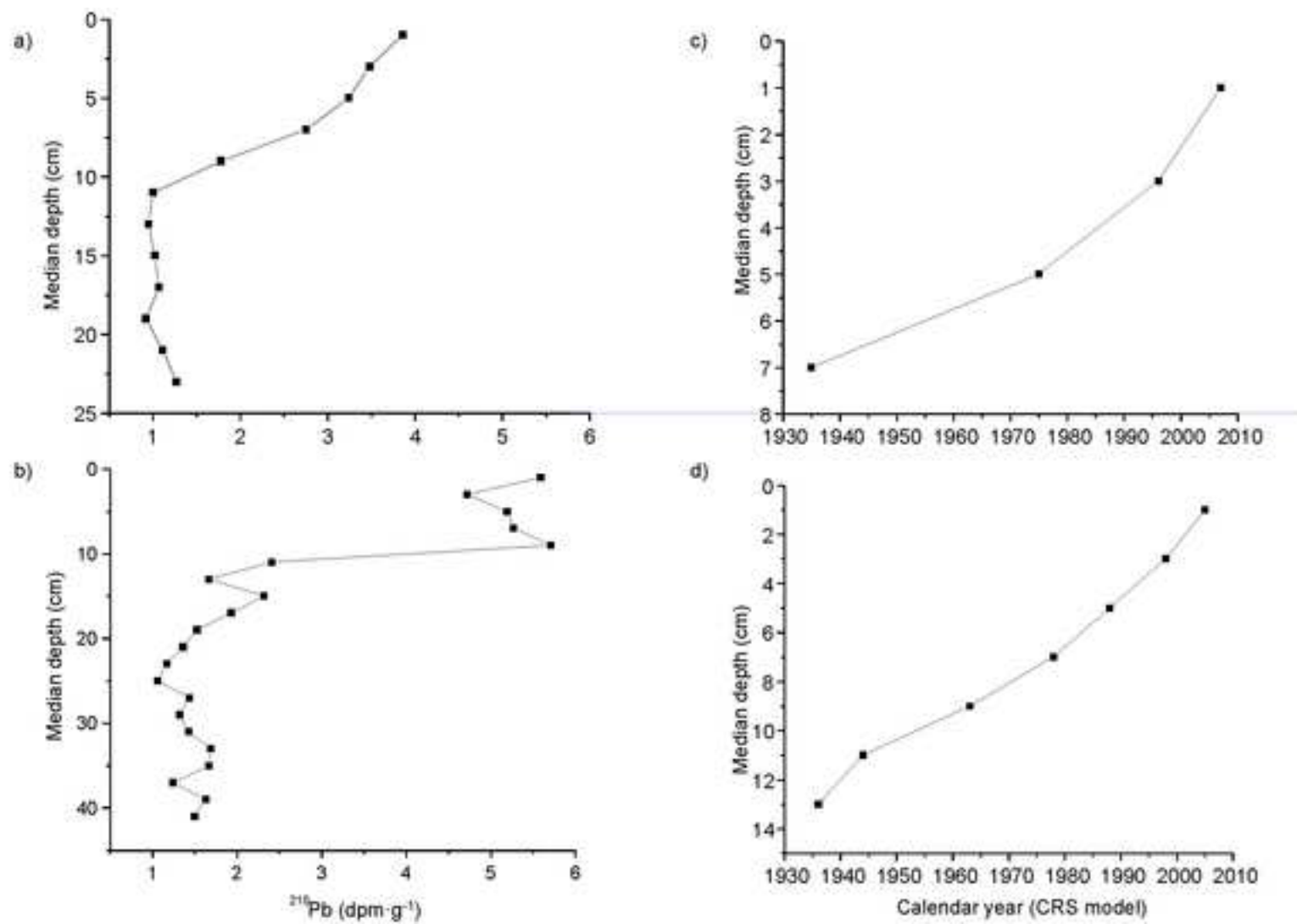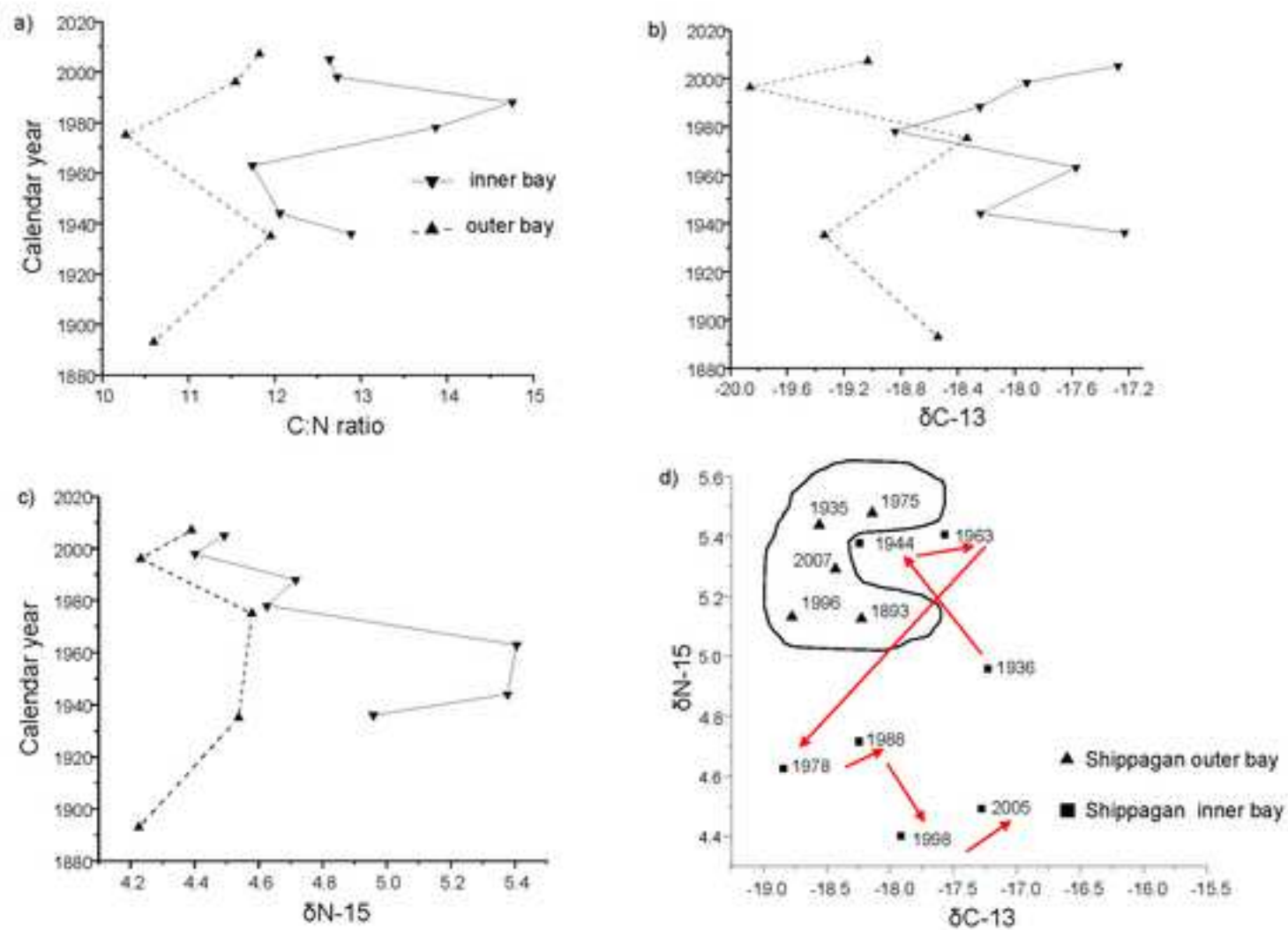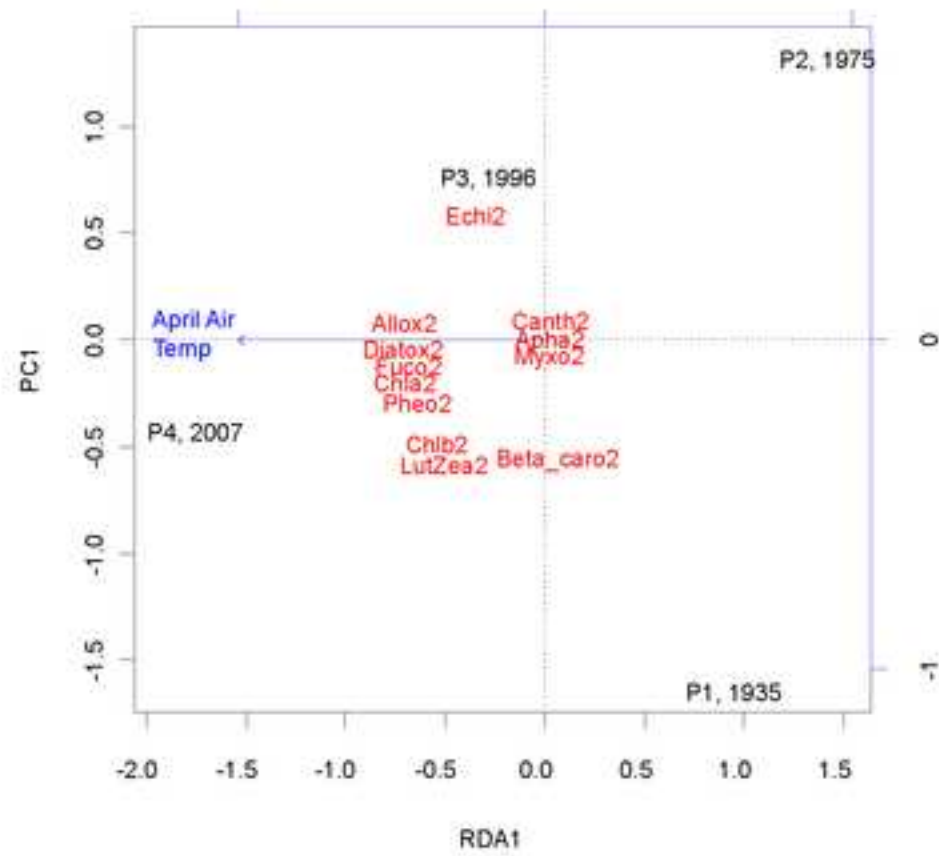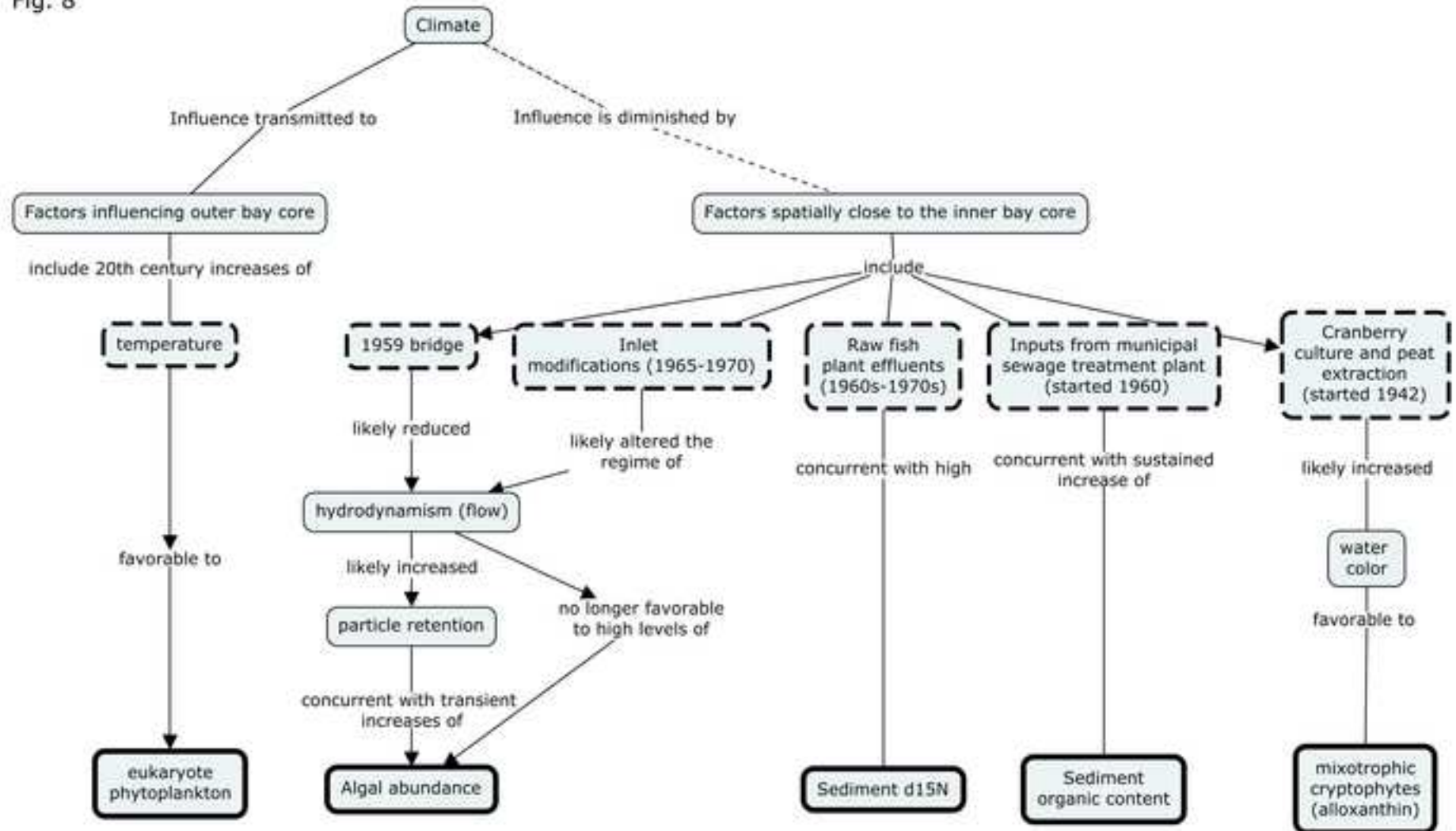
Fig. 7

Fig. 8

Online Resource 1 Timeline of selected events that potentially influenced the ecology of Shippagan Bay or that characterized Shippagan's urban and industrial development. Information relating to boardwalk construction and wastewaters is from Valmond Doiron, Shippagan Municipal Engineer (pers. comm. 2016-06-29, 2017-01-12). Population numbers were compiled from Statistics Canada. Other sources are indicated, or from Robichaud (1976), Mallet (2012)

Period	Shippagan as a whole	Shippagan northwest (NW) of the 1959 bridge ("outer bay")	Shippagan southeast (SE) of the 1959 bridge ("inner bay")
19th century to 1950s	Domestic wastewaters through "straight pipes" in the bay or to septic tanks.		
1880s			"Construction of two 300 m jetties (…) on either side of the inlet" to help navigation (Logan 2012: 76).
1898-1906		Completion of the public wharf.	
1942-1945			76 ha peat extraction southwest of bay begins; 268 Mg produced in 1942 (Warner and Buteau 2000).
1955			61 ha peat extraction begins northeast of bay.
1957-1959	Bridge construction.		
1961, summer	Shippagan municipality population reaches 1631.		First lagoon begins operation; effluents are directed into inner bay's "Baie Sauvage".
1965-1969			Addition of a new 90-m jetty stretching to the south-west on the east side of the inlet (Logan 2012).

Period	Shippagan as a whole	Shippagan northwest (NW) of the 1959 bridge ("outer bay")	Shippagan southeast (SE) of the 1959 bridge ("inner bay")
1966-1970			Construction of a 600 m long curved breakwater to promote self-scouring of the navigation channel.
1960s-1970s	Shippagan municipality population reaches 2069 in 1971, 2344 in 1976.	Up to five fish transformation plants direct their untreated effluents West of the bridge.	Two fish transformation plants direct their untreated effluents into the "inner bay", East of the bridge.
1980s	Shippagan municipality population reaches 2825 in 1981.		Partial failure of lagoons to comply with provincial guidelines.
1986	Shippagan municipality population decreases to 2801.		Aerators are added to lagoon no. 2 in April 1986.
1989 and 1993			Le Goulet Harbour dredging (Logan 2012).
1998-2004			Gradual collapse of the outer 40 m of the east jetty (Logan 2012).
1998-2002		2-km boardwalk construction in the outer bay.	Cranberry culture begins near northeast shore (Fig. 1) and reaches 47 ha in 2016.
2011	Shippagan municipality population declines to 2631; density: 262 km^{-2}; dwellings: 1199.	Last fish transformation plant closes down.	
2002-2015			Average effluent flow from Shippagan wastewater treatment plant into Baie Sauvage ("inner bay") is 76 L·s^{-1} (14 to 153), TP 1.1 mg·L^{-1} (0.2-2.9), N:P ratio 7.6 (by mass) .

Online Resource 2 Sub-surface water quality at coring sites on coring date August 1st,

2012

	Temp. (°C)	Salinity (%)	Turbidity (NTU)	Dissolved Oxygen (mg·L^{-1})	pH	Dissolved organic carbon (mg·L^{-1})	TN (µg·L^{-1})	TP (µg·L^{-1})	Chl-a (µg·L^{-1})
Outer Bay	22	2.8	4	7.7	8.1	2.4	< 300	21	2.6
Inner Bay	23	2.8	6	7.7	8.1	2.6	< 300	42	5.5