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Intertidal foraminifera in the *Spartina patens* floral zone of the LaHave Estuary, Canada: A baseline for assessing organic pollution remediation

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ABSTRACT

The LaHave Estuary is polluted with domestic waste delivered via straight pipes. These are to be replaced with septic tanks. The impact of this remediation on the wider biotic community will need to be assessed. Intertidal foraminifera are ideal for mitigation assessment in the LaHave and comparable estuaries, estuary banks supporting small beds of intertidal vegetation. This paper provides a baseline for future comparisons of the total LaHave intertidal benthic foraminiferal assemblage and presents a method applicable to other estuaries. Regarding the LaHave Estuary, any biotic change must be viewed against the backdrop of other pollutants like mercury near the town of Bridgewater.

Four 10 cm^3 replicates (push cores) were taken at four sites along the estuary's eastern bank: Miller Point Peace Park (MPPP, near Bridgewater), Dayspring, Upper LaHave and East LaHave. A fifth replicate was tested for %C and %N. To constrain altitude, the replicates were taken immediately inland of a zone of the marsh grass *Spartina alterniflora*, typically among swirl-patterned (cowlicked) *S. patens*.

The washed replicates were picked clean of foraminifera, 3821 being recovered. Recovery comprised only (in rank order of abundance) *Entzia macrescens*, *Trochammina inflata* and *Miliammina fusca*. The number per replicate ranged from 29 (East LaHave) to 816 (MPPP). Scheffé's test following ANOVA showed the mean MPPP foraminiferal density to be significantly different from the other sites, which acted as a group. The most upstream assemblage was dominated by *E. macrescens*, the most downstream by *M. fusca*.

There were no significant correlations between %C, %N and the mean foraminiferal densities of species. The mean population densities per 10 cm^3 of *E. macrescens* differed between sites, (a) MPPP, (b) Dayspring and Upper LaHave, and (c) East LaHave forming non-overlapping subsets that will need to be monitored separately. *Trochammina inflata* mean population densities were distinct only at East LaHave. *Miliammina fusca* population densities presented a peculiar pattern, MPPP and East LaHave forming one group, and the intervening Dayspring and Upper LaHave sites forming another. The transformed mean proportions per site of *E. macrescens* and *T. inflata* were not significantly correlated with %C or %N, but those of *M. fusca* were positively correlated with both. It may be that high trace metal concentrations near Bridgewater are affecting foraminiferal distributions and abundances. This must be taken into account when using the benthic foraminiferal assemblage to assess the impact of the organic pollution remediation.

1. Introduction

Intertidal foraminifera associated with marsh vegetation have a long history of study (Phleger, 1970; Phleger and Walton, 1950). Work has concentrated on large marshes underlain by considerable thicknesses of sediment. Modern assemblages at such sites have been used to develop training sets for deciphering the Holocene fossil record within cores. This has allowed modelling of Holocene sea-level change (Boomer and Horton, 2006; Horton and Edwards, 2006; Scott and Medioli, 1980a, 1986). There have as yet been few attempts to develop baselines using intertidal foraminiferal communities as part of an assessment of the efficacy of pollution remediation efforts (Armynot du Châtelet and Debenay, 2010; Armynot du Châtelet et al., 2018; Morvan et al., 2004; Wilson and Hayek, 2018), and especially not along the length of

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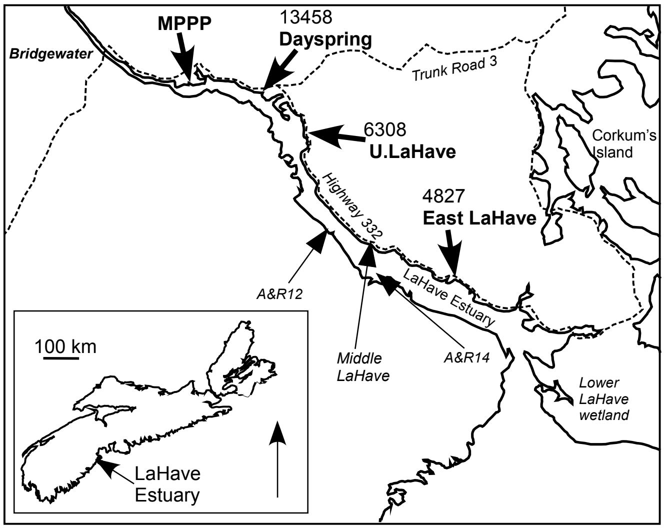

Fig. 1. The LaHave River Estuary, showing the location of the samples sites at Miller Point Peace Park (MPPP), Dayspring, Upper LaHave and East LaHave. Also shown are the Trunk Road 3, Highway 332, and two sample sites from Allen and Roda (1977; A&R12 and A&R14). The distance from MPPP to 4827 East LaHave, is 13.5 km.

estuaries, rather than at single marshes. Thus, for example, neither review of estuarine foraminifera and pollution by Alve (1995) nor by Frontalini and Coccioni (2011) mentioned intertidal foraminifera. A recent publication on conservation palaeobiology (Dietl and Flessa, 2017), which stressed an aim to return North American ecosystems to their condition prior to European settlement (Smol, 2017), did not mention foraminifera at all among its many case studies. However, estuary banks (such as those of the LaHave Estuary, Nova Scotia, studied here; 64º25'W, 44º19'N, Fig. 1) sustain more-or-less isolated, small ($< 100\,m^2$) patches of readily accessible intertidal vegetation. These patches support only a few, easily identified foraminiferal species, populations of which are ideal for monitoring environmental remediation.

Though the foraminifera to be found in these intertidal, vegetated patches have not yet been studied, those living in permanently subtidal parts of estuaries have been widely examined (see Alve, 1995, for a review of early work). Allen and Roda (1977) reported the contemporary foraminiferal assemblages from the LaHave Estuary using samples from water 1–3 m deep. Scott et al. (1980) examined foraminiferal assemblages in three Atlantic Canadian estuaries (Miramichi River and Restigouche Estuary, New Brunswick; and Chezzetcook Inlet, Nova Scotia), but used samples from a few to several tens of metres water depth. In their classification of estuarine types, Scott et al. (1980) used the data published by Allen and Roda (1977) to suggest that the LaHave Estuary is of a transitional type, ~75% of the length of the subtidal estuary being populated by transitional assemblage with abundant *Haynesina orbiculare* (upstream transitional) and *Ammotium cassis* (downstream transitional), with *Eggerlla advena* throughout this transitional zone.

Studies of subtidal foraminifera have demonstrated their usefulness in monitoring recovery from chronic pollution such as from domestic waste. Dabbous and Scott (2012) monitored benthic foraminifera in the estuarine Halifax Harbour, ~100 km east of the LaHave Estuary, before, during, and after the implementation of a municipal pollution-abatement programme. Their samples, however, were taken at water depths of 4.9–33.8 m. They noted that there were considerable changes in the subtidal fauna as a result of enhanced water treatment.

A recent meta-analysis of benthic foraminifera in transitional environments in the English Channel and southern North Sea (Armynot du Châtelet et al., 2018) discussed distributions and environmental fidelities of 37 foraminiferal indicator species in salt marshes (high, middle and low) and tidal channels. They showed that *Entzia macrescens* is a middle to high marsh species, while *Trochammina inflata* inhabits not only middle and high marshes, but tidal channels also. *Miliammina fusca* is an even more widespread species, being found in tidal channels, low, middle and high marsh. Armynot du Châtelet et al. (2018) did not, however, record the impact of pollutants on intertidal foraminiferal community composition. Tobin et al. (2005) found little evidence of test breakdown among intertidal agglutinated foraminifera in marshes despite the acidity of the sediment, and suggested that upper 1 cm slices of sediment provide assemblages representative of the marsh environment. Wilson and Hayek (2018) concluded that, because the Lower LaHave wetland they examined was affected by organic pollution from the adjacent LaHave Estuary, their data regarding total (live + dead) wetland foraminiferal assemblages formed a baseline for long-term monitoring of the progress of remediation efforts in the LaHave River. This paper builds on the suggestion of Wilson and Hayek (2018) by comparing total (live + dead) benthic foraminiferal assemblages along LaHave River estuary. It does so at four intertidal, vegetated sites, establishing a baseline for bio-monitoring the efficacy of remediation efforts that are about to commence.

2. Study area

The LaHave Estuary is fed by one of the most voluminous rivers in Nova Scotia (Webster et al., 2014). The large, tidal channel is generally deeper than 20 m, and the estuary has a high tidal exchange. These characteristics result in relatively high (25–30 on the Practical Salinity Scale) bottom-water salinities throughout the system as far upstream as the town of Bridgewater (Allen and Roda, 1977; Scott et al., 1980), 20 km from the estuary mouth. The semi-diurnal tides in the LaHave Estuary have a range of 2.5 m at Bridgewater (Webster et al., 2014). Although Bridgewater (population ~8500) is essentially a non-industrial, rural town, the LaHave Estuary is known to be polluted with trace metals (Cranston and Buckley, 1972), especially mercury, near the town. There are no publically available more up-to-date data on trace metal concentrations in the area.

The estuary is also a sink for organic matter (http://earlgrey5.wixsite.com/stellab/first-test-results), because domestic waste, including faeces, is delivered directly to the LaHave River via straight pipes. About 600 homes along the length of the river and estuary currently deliver their waste water to the river in this way, and some have done for at least half a century (Nancy Slauenwhite, oral communication). An unpublished science project presented by one of us (SMB) at the 2016 Canada Wide Science Fair noted the LaHave Estuary to contain high concentrations of enterococcal bacteria. The concentration at the time of her sampling in November 2015–February 2016 was highest at MPPP (460–1100 enterococci per 100 ml of water), and lowest at the southernmost site, the LaHave Yacht Club (67–206 enterococci per 100 ml of water). This downstream decrease may be a result of tidal flushing. These levels nevertheless exceeded Canadian health standards, which deem water with > 70 enterococci per 100 ml of water as being unfit for swimming, and warn that water with > 175 enterococci per 100 ml of water should not be allowed to touch bare skin. The Municipality has committed itself to having a Lower LaHave River free of straight pipes by 2023 (Municipality of the District of Lunenburg, 2017). It is thus anticipated that water quality in the river will improve over the next decade. Some means of monitoring the biotic impact of this remediation is required.

The banks of the LaHave Estuary support numerous small patches of intertidal vegetation with the same floral zonation as at Chezzetcook Inlet, ~140 km to the east (see Scott and Medioli, 1980a). There is low marsh, subdivided into Low Marsh B (monospecific *Spartina alterniflora*) and Low Marsh A (with admixed *S. alterniflora* and *S. patens*), and middle marsh with monospecific *S. patens*. The high marsh is occupied by *Potentilla* (cinquefoil roses), *Juncus* (reeds) and *Solidago* (goldenrods).

The study presented here concentrates on the middle marsh, which in Nova Scotia is of extremely limited vertical extent. Scott and Medioli (1980a) documented the middle marsh at Chezzetcook Inlet to occur 70–80 cm above mean sea level (camsl), while at Wallace Basin, Nova Scotia, it occurs between 52 and 56 camsl. Porter et al. (2015) determined relationships between intertidal plant species and environmental factors at sites along a range of tidal magnitudes (< 2 to > 14 m) throughout Nova Scotia. Although elevation is understood to drive vegetation types in salt marshes in the region, these authors showed that salinity can differentiate vegetation types at the same elevation. The *Spartina patens* association is characterised by high pore-water salinity (20.0 ± 0.17), intermediate elevation, and intermediate inundation times (351.7 ± 9.5 min per flooding event). At Lawrencetown, on the Atlantic coast of Nova Scotia, Porter et al. (2015) found monospecific *S. patens* middle marsh to occupy an altitudinal range of only 0.15 m, and to live at sites with a mean sediment organic matter concentration of 19.4 ± 4.67%. These monospecific beds of *S. patens* can be readily identified in the field. The weak stem base in *S. patens* bends when stressed by waves or tides (Silberhorn, 1976). When this happens to numerous, adjacent individuals, the stems intertwine, giving an overall effect of characteristic swirls, colloquially called cowlicks (Pike, 2018; Roman et al., 1984).

3. Materials and methods

Four vegetated sites were identified on the eastern bank of the LaHave Estuary downstream of Bridgewater. In our study, samples where possible were taken from within cowlicked beds of *S. patens*. The most upstream site is at the Miller Point Peace Park (MPPP), adjacent to the small carpark downstream of the cemetery (44°22′05.69″N, 64°28′55.81″W) and near the town of Bridgewater. The remaining sites can be relocated for future monitoring using the house number directly opposite the sample site along the Trunk 3 road or Highway 332: Dayspring (house number 13458; 44°22′06.47″N, 64°27′38.51″W), Upper LaHave (no. 6308; 44°21′10.11″N, 64°26′06.13″W) and East LaHave (no. 4827; 44°18′42.32″N, 64°22′31.69″W).

All sites were sampled around low tide on July 23rd, 2017. No band of flattened *S. patens* was found at East LaHave, which comprised a sheltered inlet within which the area immediately landward of the monospecific band of low marsh *Spartina alterniflora* consisted of a bladed graminoid of an indeterminate species forming tussocks ~15 cm in diameter and separated by narrow (15 cm) inter-tussock areas with soupy mud. Our samples were taken from the tussocks.

Replicate samples of the sediment between the grasses were taken by inserting a 10 cm metal push core 2.54 cm in diameter. Although Tobin et al. (2005) and Culver and Horton (2005) suggested that the top 1 cm of sediment in marshes gives an adequate representation of the total marsh foraminiferal assemblage, we retained the top 2 cm of sediment, giving a standardised replicate volume of ~10 cm^3. Four replicates were taken for foraminiferal work, and a fifth for analysis of organic carbon (%C) and nitrogen (%N) contents using infra-red spectrometry of combustion products. The five replicates were taken ~5 cm apart in a row parallel to the water's edge.

The replicates for foraminiferal work were within 36 h immersed in room temperature tap water and worked manually until as disaggregated as possible. Floating vegetable matter was decanted. The resulting residue of sediment, minor organic matter and benthic foraminifera was sieved over a 106 μm mesh to remove silt, clay and fine sand, and transferred to a steel cooking pan. Workers examining marsh foraminifera frequently pick wet samples (e.g., Kemp et al., 2012). Collins et al. (1995) picked their organic-rich residues wet without decanting any organic matter, noting that many arcellaceans may be lost. In this study the emphasis was on benthic foraminifera, the much smaller arcellaeans not being enumerated. We picked our material after drying the samples over a low (~90 °C) heat on a domestic cooking range. This killed any bacteria not removed by washing, rendering the samples safe for study. The cooled residue was transferred to Ziploc bags for subsequent study. The fifth replicate, being taken for analysis of organic matter, was not washed.

All benthic foraminifera were picked from each replicate, thus giving an indication of a foraminiferal density (FD, number of specimens per 10 cm^3 of sediment). The specimens were identified using illustrations in Scott and Medioli (1980a) and Horton and Edwards (2006).

The square root of the species count plus unity is commonly used to transform species count data but was not useful for our skewed and highly variable data. Under an assumption of a log normal distribution adjusted in the manner of Fisher to a logarithmic series, a natural logarithmic distribution reduced both the total and each of the species values into equivalent orders of magnitude for which Levene's tests showed lack of heteroscedasticity. We tested the difference of our means using ANOVA and Scheffé's test.

We attempted to obtain a historical perspective by hammering a metal pipe into the substrate to obtain longer cores to assess the nature of the foraminiferal assemblage prior to the widespread installation of straight pipes. However, we found that the fine-grained sediment is at these patches < 10 cm thick, the underlying material comprising gravelly sediment apparently placed there during trunk road and highway construction. It was not possible, therefore, to use historical ecology *sensu* Jackson and McClenachan (2017) to determine the nature of the pre-pollution foraminiferal association at intertidal sites.

4. Results

The sixteen foraminiferal replicates, totalling 16 × 10 = 160 cm^3 of sediment, yielded 3821 foraminifera (see supplementary data). The maximum foraminiferal density (FD) was 816 specimens for a replicate from the most upstream site at MPPP. The minimum FD was 29, in a replicate taken from the most downstream site at East LaHave. Overall, the mean FD was 239 foraminifera per 10 cm^3. ANOVA of the transformed FD for the entire assemblages indicated at least one site to have a significantly different mean FD ($F_{1,3} = 11.39$, $p = 0.001$). Scheffé's test showed that overall only the mean MPPP FD ($\bar{x} = 608$) was significantly different from that for each of the other sites (Dayspring, $\bar{x} = 137.5$; Upper LaHave, $\bar{x} = 121$; East LaHave, $\bar{x} = 88.75$), which acted as a group.

Of the three species of benthic foraminifera found, the most abundant (57.9% of total recovery) was *Entzia macrescens*. *Trochammina inflata* was second (28.9%) and *Miliammina fusca* (13.2%) third. A graph of the mean percentage abundances of species for each site suggests that a change in the dominant species across the four sites (Fig. 2). *Entzia macrescens* was clearly the most abundant species at MPPP, the most

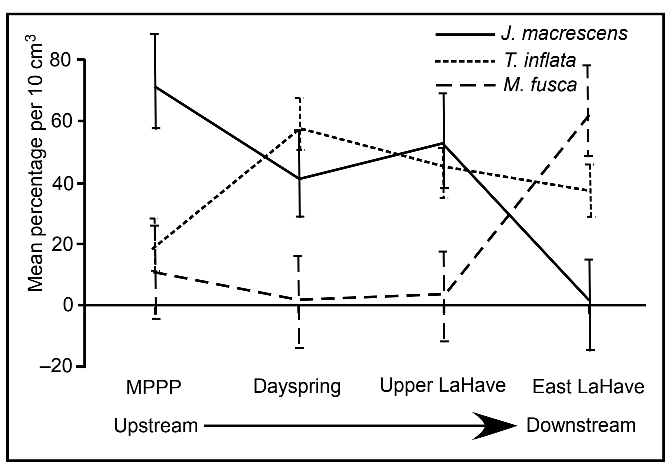

Fig. 2. A graph showing the mean percentage abundances of species for each site in the LaHave Estuary. Vertical bars show the standard error.

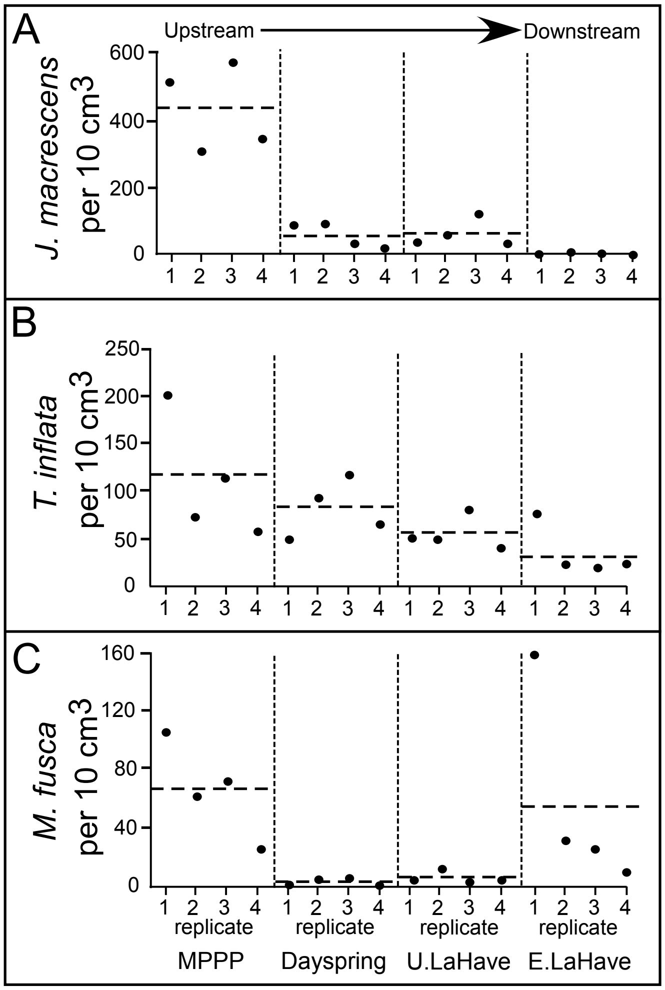

Fig. 3. The population densities per 10 cm^3 for intertidal species in the LaHave Estuary. A. *Entzia macrescens*. B. *Trochammina inflata*. C. *Miliammina fusca*. The dots indicate the population densities per 10 cm^3 replicate, while the horizontal dashed lines indicate the mean population density for the four 10 cm^3 replicates at each site.

upstream site (82.7–81.1% of the recovery from the replicates). At Dayspring and Upper LaHave *Entzia macrescens* and *T. inflata* were co-dominant. *Milliammina fusca* was dominant, and *T. inflata* subdominant, at the most downstream site at East Lahave, *E. macrescens* being proportionally rare (mean 0.28% of the four replicates, range 0–1.96%).

Regarding individual species, the ln transformed population densities per 10 cm^3 were compared between sites. The untransformed values can be read from Fig. 3. *Entzia macrescens* mean population densities were found to differ between sites ($F_{1,3} = 79.87$, $p < 0.001$; Fig. 3a), with Scheffé's test indicating (a) MPPP, (b) Dayspring and Upper LaHave, and then (c) East LaHave to form three non-overlapping subsets. *Trochammina inflata* mean population densities likewise differed between at least two sites ($F_{1,3} = 4.75$, $p = 0.021$; Fig. 3b). Scheffé's test, however, showed that only East LaHave, the most downstream site, is distinct. *Miliammina fusca* population densities differed between sites ($F_{1,3} = 12.23$, $p = 0.001$; Fig. 3c), but with a peculiar distribution; Scheffé's test showed that the two extreme upstream (MPPP) and downstream (East LaHave) are most similar, and the intervening Dayspring and Upper LaHave sites are also similar, the two groups being non-overlapping.

Transformed mean population densities for each species were compared with %C and %N (for values, see Supplementary Data, which also presents the C:N ratio) using Pearson's correlation coefficient. Values of %C ranged between 7.75 and 12.41%, but did not show a consistent pattern of change along the estuary, being highest at East LaHave and lowest at Upper LaHave. The values of %N showed the same pattern, being 0.69% at Upper LaHave and 1.18% at East LaHave. No significant correlations were found between %C, %N, the C:N ratio and the FDs of each species. While the transformed mean percentages per site of *E. macrescens* and *T. inflata* were not significantly correlated with %C or %N, those of *M. fusca* were positively correlated with both %C ($r = 0.95$, $p = 0.05$) and %N ($r = 0.97$, $p = 0.03$). There was, however, no significant correlation between the transformed mean percentages per site of any species and the C:N ratio.

5. Discussion

The intertidal foraminiferal association among *S. patens* beds and on tussocks in a comparable position changed in both abundance and proportions along the length of the estuary. *Entzia macrescens* dominated at Miller Point Peace Park (MPPP, the most upstream site), where it was at its most abundant, becoming rarer downstream and being virtually absent at East LaHave. The replicates from the downstream sites, where *Miliammina fusca* and *Trochammina inflata* were abundant, revealed a complex tessellation of small patches, some replicates as little as 5 cm apart yielding assemblages with markedly different species proportions. This mirrors the patchy nature of the middle marsh, dead foraminiferal assemblage documented by Kemp et al. (2011) and confirms the stipulation by Buzas et al. (2002), Hayek and Buzas (2010), Buzas et al. (2015) and Armynot du Chatelet et al. (2017) that multiple replicates must be taken to overcome patchiness in studies of intertidal foraminifera.

There would appear to be an increase in the niche width of dominant species downstream, at least according to the studies by Armynot du Châtelet et al. (2018) and Wilson and Hayek (2018). Armynot du Châtelet et al. (2018) showed *E. macrescens* to be restricted to middle to high marsh sites. In contrast *M. fusca,* which dominated at the most downstream site (East LaHave) inhabits low, middle and high marsh areas, and tidal channels.

It might be suggested that some of the patchiness in the LaHave Estuary arose because the replicates from East LaHave were not taken from a bed of *S. patens*, but from among a grassy tussocks in the equivalent position. However, the test results do not support this, foraminiferal densities (FDs) in replicates from Dayspring, Upper and East LaHave being similar. Application of ANOVA to FDs and Scheffé's test confirmed probabilistically that the MPPP site was significantly different from the remaining three sites, which formed a distinct group within which values of FD did not differ significantly. The *M. fusca* biofacies at East LaHave might extend even farther downstream. In their study of intertidal foraminifera in a wetland at Lower LaHave, near the LaHave estuary mouth, Wilson and Hayek (2018) found *M. fusca* to be dominant at a site among swirled *S. patens*, with lesser *T. inflata* and *Tiphotrocha comprimata*. Their sample yielded only one *E. macrescens*.

Allen and Roda (1977) examined the subtidal foraminifera within the LaHave Estuary, which Scott et al. (1980) suggested to be of a transitional type, with abundant *Haynesina orbiculare* at upstream sites and *Ammotium cassis* downstream within a transitional zone. Allen and Roda (1977, Fig. 3) suggested the transition between the *H. orbiculare* and *A. cassis* zones to occur between their sites 12 and 14, at Middle LaHave. This is considerably downstream of the transition in intertidal foraminifera FDs noted here between MPPP and Dayspring. This difference in these two transitions' positions may indicate that the subtidal and intertidal foraminiferal communities are responding differently to the environmental gradient within the LaHave Estuary. However, it is also possible that the environmental gradient within the estuary has changed over time, at least with respect to factors controlling benthic foraminiferal distributions; whereas the replicates used here were taken in 2017, Allen and Roda's (1977) samples were collected in 1976. Alternatively, the transition noted by Allen and Roda (1977) might correspond to the change to an intertidal *M. fusca* dominated biofacies between Upper and East LaHave. Finally, the small number of replicates (two per site) studied by Allen and Roda (1977) undoubtedly being insufficient to characterise any patchiness among the subtidal foraminiferal assemblages, the use of more replicates might have changed their interpretation of the subtidal part of the LaHave Estuary, confirming that transitions occur at the same position for both the intertidal and subtidal communities.

It is unclear what abiotic or biotic factors are controlling the change in assemblage composition and abundance between MPPP and the remaining study sites. It is possible that mercury pollution around Bridgewater (Cranston and Buckley, 1972) is responsible for the MPPP *E. macrescens*-rich assemblage. If so, this might indicate that *E. macrescens* has a competitive advantage over *T. inflata* and *M. fusca* at sites polluted with mercury and other trace metals. Alternatively, small differences in pore water salinity may be driving the patchiness of intertidal foraminifera within the estuary. Porter et al. (2015) found *S. patens* to occur at sites with high pore-water salinities (20.0 ± 0.17). This is lower than the salinities noted at the river surface and at 2 m water depth by Allen and Roda (1977), suggesting that there might be some admixing of saline river water and fresh ground water in the pore water within the *S. patens* beds in the LaHave Estuary. The positive correlations between the percentage of the assemblage as *M. fusca* and organic carbon and nitrogen suggest these elements might also be playing a role in controlling this species' distribution. It is unlikely that the geographical change in the intertidal foraminiferal community is driven by differences in inundation time, even though *E. macrescens* lives primarily at middle and upper marsh sites with long exposure times (Francescangeli et al., 2017); Porter et al. (2015) recorded differences in inundation times of only ~20 min at different sites with monospecific *S. patens*.

There was no correlation between the intertidal FD and either organic carbon and nitrogen concentrations. We note that the values of %C at our sites (7.75–12.41%) are somewhat lower than those of 19.4 ± 4.67% recorded by Porter et al. (2015) for monospecific beds of *S. patens* elsewhere in Nova Scotia, but are on the same order of magnitude.

The bacterial samples collected by SMB and the foraminiferal samples presented here were taken at different times and seasons (winter vs. summer). The foraminiferal samples were collected when carrying capacity for intertidal foraminifera was likely to be at its highest in the LaHave Estuary (cf. Wilson and Horton, 2012). Nevertheless, the *post mortem* destruction of intertidal foraminiferal tests being limited at temperate latitudes (Scott and Medioli, 1980b), the number of dead specimens greatly outweighs the number of live ones and the total assemblage incorporates all seasonal variations (Albani and Johnson, 1976). Despite the limited impact of the live community on the composition of the total assemblage, we think it unwise, in view of these differences in the sampling times, to invoke bacterial concentrations as a major cause for the change in the foraminiferal assemblage composition and abundance between MPPP and Dayspring without further investigation. The concordance of foraminiferal and bacterial sampling times is thus of major importance for future work and remediation identification in this area.

The suggestion by Scott and Medioli (1980b) that the total assemblage of marsh foraminifera is dominated by dead specimens implies that sites might for monitoring purposes be sampled at any convenient time of year. However, we recommended for reliability of measurement that the assemblage be sampled at the same time annually. Using total assemblages means, however, that monitoring the impact of environmental remediation on the intertidal foraminiferal community might have to take place over a number of years, if not decades, in a similar manner to the FORAM Index of Hallock et al. (2003), rather than annual sampling suggested for live foraminifera as per the FOBIMO protocol (Schönfeld et al. (2012). Annual sampling might be useful, however, to detect if any new species appear during the recovery.

It not being possible to obtain more extensive push cores, we could not determine the nature of the foraminiferal assemblage prior to the widespread permanent settlement of the estuary banks. It might be suggested that coring in the wetland studied by Wilson and Hayek (2018) will be able to give at least some indication of the pre-settlement assemblage, at least close to the estuary mouth. Such coring of the lower LaHave wetland is unlikely, however, to provide a record extending back to pre-straight pipes time. As noted by Wilson and Hayek (2018), most sedimentation in the Lower LaHave wetland has occurred within the last ~150 years, the site of the wetland being shown as an open inlet on the topographic map of Church (1864). We expect that coring within the subaqueous parts of the main channel of the LaHave Estuary, perhaps at depths comparable to those sampled by Allen and Roda (1977), will have a greater chance of furnishing material from pre-straight pipe time.

6. Conclusion

Intertidal foraminifera, with their great abundance, low species number and ease of identification, will provide an ideal tool for monitoring the impact of changes in the water quality on the wider ecosystem in the LaHave Estuary following the removal of the straight pipes. Our work suggests that, at least with respect to intertidal foraminiferal abundance, the LaHave Estuary comprises two zones, one being found at Miller Point Peace Park, and the other at sites from Dayspring downstream. We suggest that intertidal and subtidal foraminiferal densities be monitored in both these areas to assess the impact of remediation. The use of total foraminiferal assemblages, as opposed to live ones, will remove any complications that might arise from seasonality. It will, however, require that monitoring take place over a number of years, if not even decades, as changes in the live assemblage become incorporated into the total assemblage. We found that the composition of the middle marsh assemblage changed along the length of the estuary, being dominated by *Entzia macrescens* upstream and *Miliammina fusca* downstream. This might reflect the impact of heavy metal pollution near Bridgewater. However, long term monitoring will assess if there are any changes in assemblage composition over time at the sample sites. We anticipate that the remediation in the LaHave estuary will lead to similar pollution mitigation programmes elsewhere in Nova Scotia, such as in the nearby Mersey Estuary, if not even elsewhere throughout Atlantic Canada. Baselines such as the one presented here can be developed for other estuaries prior to the instigation of the pollution mitigation programmes, and compared with that for the LaHave Estuary. These baselines can then be used to examine the rehabilitation programmes' effect on the wider biotic community.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2018.08.028.

References

Albani, A.D., Johnson, K.R., 1976. Resolution of foraminiferal biotopes in broken bay, new South Wales. J. Geol. Soc. Aust. 22, 435–446.

Allen, R., Roda, R.S., 1977. Benthonic foraminifera from Lahave estuary. Marit. Sediments 13 (2), 67–72.

Alve, E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. J. Foraminifer. Res. 25, 190–203.

Armynot du Châtelet, É., Debenay, J.-P., 2010. The anthropogenic impact on the western French coasts as revealed by foraminifera: a review. Rev. Micropaleontol. 53, 129–137.

Armynot du Châtelet, É., Francescangeli, F., Bouchet, V.M.P., Frontalini, F., 2018. Benthic foraminifera in transitional environments in the English Channel and the southern North Sea: a proxy for regional-scale environmental and paleo-environmental characterisations. Mar. Environ. Res. 137, 37–48.

Armynot du Chatelet, É., Frontalini, F., Francescangeli, F., 2017. Significance of replicates: environmental and paleoenvironmental studies on benthic foraminifera and testate amoebae. Micropaleontology 63, 257–274.

Boomer, I., Horton, B.P., 2006. Holocene relative sea-level movements along the North Norfolk coast, UK. Palaeogeogr. Palaeoclimatol. Palaeoecol. 230, 32–51.

Buzas, M.A., Hayek, L.C., Jett, J.A., Reed, S.A., 2015. Pulsating patches: history and analyses of spatial, seasonal, and yearly distribution of living benthic foraminifera. Smithsonian Contrib. Paleobiol. 97, 1–91.

Buzas, M.A., Hayek, L.-A.C., Reed, S.A., Jett, J.A., 2002. Foraminiferal densities over five years in the Indian River lagoon, Florida: a model of pulsating patches. J. Foraminifer. Res. 32, 68–92.

Church, A.F., 1864. In: Topographic Township Map of Lunenburg County, Nova Scotia, from Actual Surveys Made, Drawn and Engraved by and under the Direction of A. F. Church. A. F. Church and Co., Bedford, Nova Scotia.

Collins, E.S., Scott, D.B., Gayes, P.T., Medioli, F.S., 1995. Foraminifera in Winyah Bay and North Inlet marshes, South Carolina; relationship to local pollution sources. J. Foraminifer. Res. 25, 212–223.

Cranston, R.E., Buckley, D.E., 1972. Mercury pathways in a river and estuary. Environ. Sci. Technol. 6, 274–278.

Culver, S.J., Horton, B.P., 2005. Infaunal Marsh Foraminifera from the Outer Banks, North Carolina, U.S.A. J. Foraminifer. Res. 35, 148–170.

Dabbous, S.A., Scott, D.B., 2012. Short-term monitoring of Halfiax Harbour (Noca Scotia, Canada) pollution remediation using benthonic foraminifera as proxies. J. Foraminifer. Res. 42, 187–205.

Dietl, G.P., Flessa, K.W., 2017. Conservation Paleobiology: Science and Practice. University of Chicago Press, Chicago, USA.

Francescangeli, F., Bouchet, V.M.P., Trentesaux, A., Armynot du Chatelet, É., 2017. Does elevation matter? Living foraminiferal distribution in a hyper tidal salt marsh (Canche Estuary, Northern France). Estuarine. Coast. Shelf Sci. 194, 192–204.

Frontalini, F., Coccioni, R., 2011. Benthic foraminifera as bioindicators of pollution: A review of Italian research over the last three decades. Rev. Micropaleontol. 54, 115–127.

Hallock, P., Lidz, B., Cockey-Burkhard, E.M., Donnelly, K.B., 2003. Foraminifera as bioindicators in coral reef assessment and monitoring: The FORAM Index. Environ. Monit. Assess. 81, 221–238.

Hayek, L.-A.C., Buzas, M.A., 2010. Surveying Natural Populations: Quantitative Tools for Assessing Biodiversity. Columbia University Press, New York, USA, pp. 590.

Horton, B.P., Edwards, J.C., 2006. Quantifying Holocene Sea-level Change Using Intertidal Foraminifera: Lessons from the British Isles, vol. 40. Cushman Foundation for Foraminiferal Research, Special Publication, pp. 1–97.

Jackson, J.B.C., McClenachan, L., 2017. Historical ecology of the paleontologist. In: Dietl, G.P., Flessa, K.W. (Eds.), Conservation Paleobiology: Using the Past to Manage for the Future. The University of Chicago Press, Chicago, USA, pp. 87–100.

Kemp, A.C., Buzas, M.A., Horton, B.P., Culver, S.J., 2011. Influence of patchiness on modern salt-marsh foraminifera used in sea-level studies (North Carolina, USA). J. Foraminifer. Res. 41, 114–123.

Kemp, A.C., Horton, B.P., Vann, D.R., Engelhart, S.E., Grand Pre, C.A., Vane, C.H., Nikitina, D., Anisfeld, S.C., 2012. Quantitative vertical zonation of salt-marsh foraminifera for reconstructing former sea level; an example from New Jersey, USA. Quat. Sci. Rev. 54, 26–39.

Morvan, J., Le Cadre, V., Jorissen, F., Debenay, J., 2004. Foraminifera as potential bioindicators of the "Erika" oil spill in the Bay of Bourgneuf: Field and experimental studies. Aquat. Living Resour. 17, 3187–3322.

Municipality of the District of Lunenburg, 2017. LaHave River Straight Pipe Replacement Program. https://www.modl.ca/i-want-to/know-more-about/lahave-river-cleanup, Accessed date: 12 December 2017.

Phleger, F.B., 1970. Foraminiferal populations and marine marsh processes. Limnol. Oceanogr. 15, 522–534.

Phleger, F.B., Walton, W.R., 1950. Ecology of marsh and bay foraminifera, Barnstable, Massachusetts. Am. J. Sci. 248, 274–294.

Pike, S., 2018. Nature News: the Curious Cowlicks of Salt Marsh hay. http://www.fosters.com/news/20180319/nature-news-curious-cowlicks-of-salt-marsh-hay, Accessed date: 29 April 2018.

Porter, C., Lundholm, J., Bowron, T., Lemieux, B., van Proosdij, D., Neatt, N., Graham, J., 2015. Classification and environmental correlates of tidal wetland vegetation in Nova Scotia, Canada. Botany 93, 825–841.

Roman, C.T., Niering, W.A., Warren, R.S., 1984. Salt marsh vegetation change in response to tidal restriction. Environ. Manag. 8, 141–149.

Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., group, M. o. t. F., 2012. The FOBIMO (FOraminiferal BIo-MOnitoring) initiative—Towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies. Mar. Micropaleontol. 94–95, 1–13.

Scott, D.B., Medioli, F.S., 1980a. Quantitative Studies of Marsh Foraminiferal Distributions in Nova Scotia: Implications for Sea Level Studies, vol. 17. Cushman Foundation for Foraminiferal Research Special publication, pp. 1–58.

Scott, D.B., Medioli, F.S., 1980b. Living vs. total foraminiferal populations: their relative usefulness in paleoecology. J. Paleontol. 54, 814–831.

Scott, D.B., Medioli, F.S., 1986. Foraminifera as sea-level indicators. In: van de Plassche, O. (Ed.), Sea-level Research: a Manual for the Collection and Evaluation of Data. Geo Books, Norwich, UK, pp. 435–455.

Scott, D.B., Schafer, C.T., Medioli, F.S., 1980. Eastern Canadian estuarine foraminifera; a framework for comparison. J. Foraminifer. Res. 10, 205–234.

Silberhorn, G.M., 1976. Tidal Wetland Plants of Virginia, Gloucester Point. Virginia Institute of Marine Science, College of William and Mary, Virginia, USA, pp. 86.

Smol, J.P., 2017. Conservation biology and environmental change: A paleolimnological perspective. In: Dietl, G.P., Flessa, K.W. (Eds.), Conservation Paleobiology: Science and Practice. University of Chicago Press, Chicago, USA, pp. 31–44.

Tobin, R., Scott, D.B., Collins, E.S., Medioli, F.S., 2005. Infaunal benthic foraminifera in some North American marshes and their influence on fossil assemblages. J. Foraminifer. Res. 35, 130–147.

Webster, T., McGuigan, K., Collins, K., MacDonald, C., 2014. Integrated river and coastal hydrodynamic flood risk mapping of the LaHave river estuary and town of Bridgewater, Nova Scotia, Canada. Water 6, 517–546.

Wilson, B., Hayek, L.C., 2018. A study of co-occurrences of foraminifera and mussels in a polluted Nova Scotian wetland, Atlantic Canada. J. Foraminifer. Res. 48, 164–171.

Wilson, B., Horton, B.P., 2012. Determining carrying capacity from foraminiferal time series. J. Micropalaeontol. 31, 111–119.