A multi-proxy modern training set for reconstructing Holocene relative sea level using salt-marsh sediment (Prince Edward Island, Canada)

- 3
- Andrew C. Kemp^{1*}, Robin J. Edwards², Fermin Alvarez-Agoues², Emmanuel Bustamante¹, Zoë
 A. Roseby^{2,3}, Andrea D. Hawkes⁴, and Philip L. Woodworth⁵
- 6

7

- 1. Department of Earth and Climate Sciences, Tufts University, Medford, MA 02155, USA
- 2. School of Natural Sciences, Trinity College Dublin, Dublin, Ireland
- 3. Department of Earth and Environmental Science, University of Exeter, Penryn, UK
- Department of Earth and Ocean Sciences, University of North Carolina Wilmington,
 Wilmington, NC 28403, USA
- 12 5. National Oceanography Centre, Liverpool, UK
- 13
- 14 *Corresponding author: andrew.kemp@tufts.edu; +1 617-627-0869

15 Abstract

16 Reconstructing Holocene relative sea-level change from salt-marsh sediment requires a modern 17 training set that captures the observable relationship between proxies and local tidal elevation. 18 We collected 143 surface sediment samples from four salt marshes in Prince Edward Island (PEI, 19 Canada) to develop a modern training set of foraminifera and bulk-sediment δ^{13} C and δ^{15} N 20 values. Two sites have semi-diurnal tidal regimes, one has a mixed regime, and one has a diurnal 21 regime. Combining and standardizing datasets from different tidal regimes fails to adequately 22 characterize the relationship between elevation and inundation. Our principal results are from the 23 semi-diurnal sites. Salt-marsh foraminifera in PEI form low-diversity, elevation-dependent zones 24 that are replicated within sites, among sites, and between two studies conducted 44 years apart. 25 Botanical zonation of PEI salt marshes often includes a platform with C₄ plants and an adjacent, 26 higher transitional community of C₃ plants. Bulk-sediment δ^{13} C values mirror the dominant 27 vegetation. Isotopic results from PEI are combined with datasets from Delaware to 28 Massachusetts to explore how elevation thresholds and $\delta^{13}C$ cut-off values can recognize 29 environments of deposition. We propose that δ^{13} C values more negative than -20.0‰ indicate 30 formation above an elevation threshold placed slightly below mean higher high water, while $\delta^{13}C$ 31 values less negative than -17.0% characterize environments lower than an elevation threshold 32 slightly above mean higher high water. Bulk-sediment $\delta^{15}N$ values display a correlation with 33 tidal elevation and botanical zone, but may be subject to anthropogenic and post-depositional 34 modification limiting their utility as a sea-level proxy. The dataset of modern foraminifera is suitable for reconstructing relative sea level and could be combined with informative δ^{13} C values 35 36 in a multi-proxy approach.

37 Keywords: Foraminifera, δ^{13} C, δ^{15} N, tidal regime, tidal range

38 1. Introduction

39 Low-energy coasts in eastern North America are characterized by the presence of salt marshes at 40 intertidal elevations. Height-dependent differences in the frequency and duration of (primarily) 41 tidal submergence give rise to a pronounced biogeochemical gradient across the elevational 42 range of the salt marsh. The most visible expression of this gradient is the vertical zonation of 43 botanical sub-communities (Bertness 1991; Johnson and York 1915), but assemblages of 44 microorganisms (e.g., foraminifera; Scott and Medioli 1978), and sediment composition (e.g., 45 organic content, isotopic ratios, and grain size; Chmura and Aharon 1995; Plater et al. 2015) can 46 also exhibit systematic relationships to tidal elevation, indicating that they are potential sea-level 47 proxies. Under conditions of sustained relative sea-level (RSL) rise, sediment accumulates on the 48 salt-marsh surface and thickens through time into a stratigraphic archive. Proxies preserved in 49 this buried sediment are used to reconstruct paleomarsh elevation (and subsequently RSL) 50 through reasoning by analogy (Shennan 2015). This approach is predicated on using 51 observations from modern salt marshes to establish the relationship between each sea-level proxy 52 and tidal elevation. Therefore, constructing a modern training set of appropriate spatial and 53 ecological scope to quantitatively test and demonstrate the utility of potential sea-level proxies is 54 a necessary early step in reconstructing RSL (Horton and Edwards 2006; Williams et al. 2021).

55

Efforts to reconstruct subtle (relatively small and short-lived) changes in late Holocene RSL rely
on quantitative analysis of sea-level proxies with a precise relationship to tidal elevation (Gehrels
et al. 2020). Salt-marsh foraminifera are well-established and widely-used sea-level proxies
because they form elevation-dependent assemblages comprised of several taxa and many
individuals (Edwards and Wright 2015). Transfer functions formalize taxon-elevation

61 relationships and when applied to assemblages preserved in buried (and dated) sediment yield 62 quantitative RSL reconstructions. This approach treats tidal elevation as a continuous variable 63 and is therefore advantageous for examining Holocene RSL compared to approaches (e.g., 64 qualitative recognition of high salt-marsh sediment) that recognize only discrete elevation zones 65 (Kemp and Telford 2015; Vacchi et al. 2018). Bayesian transfer functions (BTF) offer a further 66 development in the pursuit of accurate and precise RSL reconstructions by accommodating 67 results from proxies in addition to foraminifera through adopting informative priors (Cahill et al. 68 2016; Kemp et al. 2024; Kemp et al. 2018; Stearns et al. 2023). In this capacity, proxies that 69 resolve discrete tidal elevation when examined in isolation can help to refine near-continuous 70 RSL records when applied in the multi-proxy framework of a BTF. Furthermore, discrete sea-71 level proxies even with relatively low precision may improve the vertical resolution of RSL 72 reconstructions if they occupy different, but overlapping, ranges with complementary proxies 73 (Kemp et al. 2018; Walker et al. 2023).

74

75 On some parts of the Atlantic coast of North America, δ^{13} C provides valuable prior information 76 for BTFs because high salt-marsh platforms (occupying a discrete range between approximately 77 mean tide level, MTL, and mean higher high water, MHHW) are natively vegetated by plants 78 utilizing the C₄ photosynthetic pathway (Johnson et al. 2007; Kemp et al. 2012; Middleburg et al. 79 1997). These C₄ plants discriminate less strongly against 13 CO₂ during photosynthesis than the 80 C₃ plants that live above MHHW (Lamb et al. 2006). The resulting isotopic difference between 81 these two zones is large and well preserved in bulk sediment (Chmura and Aharon 1995; Ember 82 et al. 1987; Fogel et al. 1989; Lamb et al. 2006), which facilitates recognition of sediment that 83 likely accumulated above/below the ~MHHW threshold. Simultaneous measurement of multiple

84 elements on modern instruments offers an opportunity to evaluate the utility of other isotope 85 systems as sea-level proxies in salt-marsh environments. Salt-marsh plants at sites around the world are characterized by elevated δ^{15} N values compared to upland plants (Cloern et al. 2002; 86 87 Peterson et al. 1985), which has been exploited to trace organic matter in coastal food webs 88 (Kwak and Zedler 1997), including grazing of domesticated herbivores on salt-marsh grasses 89 (Britton et al. 2008; Guiry et al. 2021). Similarly, δ^{15} N values may have utility in recognizing 90 bulk sediment preserved in the coastal stratigraphic record that accumulated in a salt marsh (or 91 salt-marsh sub-zone) and can therefore be employed as a sea-level proxy (Engelhart and Horton 92 2012).

93

94 Salt marshes on Prince Edward Island (PEI), Canada (Figure 1) likely preserve a detailed history 95 of RSL change (Scott et al. 1981; Vacchi et al. 2018), which would contribute to ongoing efforts 96 to better understand the spatio-temporal pattern and causes of Holocene RSL variability. As an 97 early step in reconstructing RSL on PEI, we aim to: (1) develop a modern training set of salt-98 marsh foraminifera using new and existing (Scott et al. 1981) observations; (2) test if bulk 99 sediment δ^{13} C can help inform RSL reconstructions by establishing appropriate elevation 100 thresholds and cut-off values for PEI; and (3) evaluate the possible use of bulk-sediment δ^{15} N as 101 a sea-level proxy. Our new data, comprises seven surface transects from four sites (143 total 102 samples). We show that common approaches to combine sites with different tidal ranges are 103 inappropriate for merging observations from different tidal regimes (e.g., mixed or diurnal vs 104 semi-diurnal). Within- and among-site variability of foraminiferal assemblages is modest and 105 two investigations conducted 44 years apart document consistent zonation of foraminifera. An expanded and standardized dataset of δ^{13} C values differentiates between bulk sediment that 106

107	accumulated above (δ^{13} C more negative than –20.0‰) and below (δ^{13} C less negative than –
108	17.0‰) approximately MHHW. Through sensitivity testing, we propose adopting an elevation
109	threshold between these two botanical zones that is transitional (rather than a singular plane)
110	around MHHW. This result is likely representative of sites between approximately Delaware and
111	the Canadian Maritimes where salt marshes are natively dominated by C ₄ plants (Wilson et al.
112	2024). Surface bulk-sediment δ^{15} N displays a relationship to vertically-ordered botanical zones,
113	but its utility as a sea-level proxy may be limited by anthropogenic modification and post-
114	depositional fractionation.
115	
116	2. Study Area and Previous Work
117	On PEI (Figure 1) salt marshes occur within estuaries, low-energy bays, and behind the
118	protection of sand bars and spits. Typically, unvegetated tidal flats meet the salt-marsh platform
119	at a steep cliff or creek bank that displays visible evidence of slumping and erosion. A narrow
120	band of Spartina alterniflora (C ₄ plant) characterizes the edge of the cliff or creek bank levees.
121	The broad, low-relief, salt-marsh platform is vegetated by Spartina patens and Distichlis spicata
122	(C ₄ plants), although small patches of stunted Spartina alterniflora occur in depressions and
123	other poorly drained locations. A more diverse community of C3 plants occurs at the brackish
124	transition from salt-marsh platform to freshwater upland and this zone includes Carex palaeacea,
125	luncus garardii Anium gravoolans. Typha gugustifolia, Atriplay patula, and Potantilla sp. Wo
	Suncus gerurun, Apium gruveolens, Typnu uugustijonu, Airiptex pututu, and Totentitu sp. WC

- 127 the Atlantic coast of North America and we noted patches of draped sediment on the salt-marsh
- 128 surface in the vicinity of creek margins at some sites. We tentatively attribute this pattern to ice
- 129 rafting of frozen creek-bed sediments (Argow et al. 2011; FitzGerald et al. 2020).

131	Tidal regimes and ranges vary markedly around the coast of PEI. This variability arises from the
132	interaction of the North Atlantic semi-diurnal tidal wave (which enters the Gulf of St. Lawrence
133	through the Cabot Strait) with an amphidromic system close to the Magdalen Islands and a
134	secondary amphidrome in Northumberland Strait (Lu et al. 2001; Pugh and Woodworth 2014;
135	Figure 1A). Consequently, the sum of the principal lunar (M2) and solar (S2) semi-diurnal
136	components increases from ~0.15 m at West Point to ~0.92 m at Charlottetown. In contrast, the
137	sum of the principal diurnal components (O1 + K1) changes from ~0.45 m to ~0.47 m over the
138	same distance. The form factor (FF) describes tidal regime and is calculated as $(O1 + K1) / (M2)$
139	+ S2). A FF>3 describes a diurnal regime (e.g., West Point where FF=3.05 and great diurnal tidal
140	range is 0.71 m; Figure 1), FF 3.0–1.5 is a mixed, but mainly diurnal regime (e.g., Cape Egmont
141	where FF=1.57 and great diurnal tidal range is 0.96 m Figure 1), FF 1.5–0.25 is a mixed, but
142	mainly semi-diurnal regime, and FF<0.25 is a semi-diurnal regime. For simplicity, we describe
143	Cape Egmont (for the site at Haldimand River) as a mixed regime and Victoria (FF=0.48 and
144	great diurnal tidal range of 1.86 m; for the Tryon and Augustine sites) and Charlottetown
145	(FF=0.51) as semi-diurnal.

146

A compilation of sea-level index points suggests that RSL in PEI rose at approximately 1 mm/yr
during the past 2000 to 3000 years as a consequence of ongoing glacio-isostatic adjustment
(GIA; Vacchi et al. 2018). This sustained rate of rise enabled thick sequences of salt-marsh
sediment to accumulate at sites, particularly along the coast of Northumberland Strait (Scott et al.
1981; Figure 1). Since 1911, the (linear, centennial-scale) rate of RSL rise measured by the
Charlottetown tide gauge was 3.3 mm/yr (Figure 1).

154	During summer 2022 CE, we sampled four salt marshes (Figure 1) in contrasting geomorphic
155	settings to investigate within- and among-site variability of sea-level proxies. The Tryon
156	saltmarsh is located \sim 2 km from the open coast along the Tryon River, which has an open
157	connection to Northumberland Strait (Figure 1D). We selected this site because Scott et al.
158	(1981) described modern foraminifera and reported up to 5 m of salt-marsh peat in the
159	underlying stratigraphy, which radiocarbon dating suggests accumulated at ~1 mm/yr. This is the
160	thickest and oldest sequence of salt-marsh peat reported by Scott et al. (1981) across the 45 sites
161	around PEI that they investigated. Tidal flats in the Tryon River are unvegetated mud and meet
162	the high salt-marsh platform (Spartina patens and Distichlis spicata) at a steep creek bank.
163	Augustine was chosen to investigate among-site variability because of its proximity (~5 km) to
164	Tryon. The tidal channel at Augustine is narrow and characterized by a dynamic flood tide delta
165	at its connection to Northumberland Strait (Figure 1G). The sediment comprising this delta and
166	seaward tidal flats is coarse, inorganic sand. A community of Spartina patens and Distichlis
167	spicata characterizes the salt-marsh platform. At the transition from salt marsh to upland there
168	are some parts of the site with Typha augustifolia and others where Carex palaeacea is more
169	prevalent. The tide gauge at Victoria (Figure 1) is the closest available for both Tryon and
170	Augustine.

171

We selected the Wolfe Inlet site because Scott et al. (1981) described modern foraminifera from
this location and reported up to 1.2 m of salt-marsh peat in the stratigraphic record. The
saltmarsh is protected from Egmont Bay by a dynamic sand barrier (Fig. 1B, 1E). A small cliff
separates the salt marsh from the sandy tidal flats of the inlet, while extensive pond holes and

176 uneven topography characterise the marsh platform. The plant community on the salt-marsh 177 platform is notable because it includes an unusually high abundance (compared to the other sites) 178 of *Carex palaeacea* and *Juncus geradii* with a correspondingly low abundance of *Spartina* spp. 179 and *Distichlis spicata*. Through conversations with experienced fishermen at the site, we learned 180 that the salt marsh likely experienced pronounced geomorphic change including loss of salt-181 marsh area between the sampling by Scott in summer 1978 CE and our sampling in summer 182 2022 CE. Aerial images available through Google Earth indicate that an inlet opened in the 183 barrier at Wolfe Inlet some time between 1986 and 2006. During reconnaissance coring at Wolfe 184 Inlet, we found no more than ~ 0.8 m of salt-marsh peat and propose that the thicker sequences 185 were eroded during the recent geomorphic evolution of the site. The West Point tide gauge is the 186 closest to Wolfe Inlet (Figure 1).

187

The Haldimand River site is situated in an open estuary and was chosen because Scott et al.
(1981) reported up to 1.5 m of salt-marsh peat underlying the nearby Jacques River site (but did
not collect modern samples of foraminifera). This site lacks tidal flats and there is a pronounced
step between the river and salt-marsh platform (vegetated by *Spartina patens* and *Distichlis spicata*). Several large parts of the marsh are degraded and characterised by extensive pond holes
and irregular, low elevation, partially-vegetated surfaces. The Cape Egmont tide gauge is the
closest to Haldimand River (Figure 1).

195

196 In addition to Tryon and Wolfe Inlet, Scott et al. (1981) reported counts of modern salt-marsh

197 foraminifera at two other sites (Percival River and Mt. Stewart; Figure 1) that we did not

198 resample because: (1) no elevation data are available (both sites); (2) the location of Mt. Stewart

199	in the upper reaches of the Hillsborough River suggests a high likelihood that local tides are
200	distorted compared to those at the coast; and (3) there is a lack of nearby tide gauges to reliably

establish local tidal datums.

202

3. Materials and Methods

204 *3.1 Sampling regime*

205 We selected four sites in PEI with contrasting geomorphologies and tidal characteristics (range 206 and regime) to construct a multi-proxy modern training set in support of efforts to reconstruct 207 Holocene RSL. By revisiting two sites (Tryon and Wolfe Inlet) where Scott et al. (1981) sampled 208 surface for aminifera in 1978 CE we are able to evaluate if changes in assemblage occurred over 209 a period of 44 years. The proximity of Tryon and Augustine offers an opportunity to evaluate 210 among-site variability, while collection of samples along two transects within three of the four 211 sites is the basis for evaluating within-site variability in sea-level proxies. 212 213 Surface samples were collected in June 2022 CE along transects extending from tidal flats to

above the apparent limit of marine influence. At each sampling station, two samples of surface

215 (0–1 cm) sediment were collected. A sample for foraminiferal analysis was placed into a vial of

216 buffered, ~30% ethanol and stained with rose Bengal to differentiate between individuals that

217 were living or dead at the time of collection (Walton 1952). A sample for bulk sediment analysis

218 was placed into a sealed plastic bag. All samples were stored in refrigerated darkness until

analysis.

220

221 *3.2 Tidal datums and levelling*

At each site, we installed an automated logger at low tide to measure water-level variability at six-minute time intervals. An additional logger simultaneously measured air pressure variability that was subsequently used to correct the water-level data for atmospheric effects. Water levels measured by the loggers were correlated with observations from nearby tide gauges to establish elevations relative to local tidal datums. The water loggers served as temporary benchmarks for levelling (Woodroffe and Barlow 2015). We used a total station to measure the elevation of the surface samples to the water loggers (and by extension local tidal datums).

229

230 3.3 Foraminiferal analysis

231 On return to the laboratory, samples for foraminiferal analysis were sieved under running water 232 to retain the 63-500 µm fraction. Foraminifera were examined in suspension beneath a binocular 233 microscope with a target count size of 100 dead tests (Kemp et al. 2020; Walker and Cahill 234 2024). We adopted a minimum count of 30 dead tests as the threshold for the presence of 235 foraminifera (Anisfeld et al. 2019; Garrett et al. 2022). Our taxonomy follows Edwards and 236 Wright (2015), but notably we combined counts of Jadammina macrescens and Balticammina 237 pseudomacrescens into a single taxon (JmBp). We retain use of Jadammina macrescens rather 238 than Entzia macrescens (Filipescu and Kaminski 2008) because of its ubiquity in the salt-marsh 239 and sea-level literature. We combined species into genus-level taxon for Haplophragmoides spp. 240 and also for *Ammobaculites* spp. All calcareous tests were placed into a single taxon.

242	Scott et al. (1981) tabulated the abundance of foraminifera as percentages of live and total
243	assemblages and density of tests. In replicated samples test density frequently varies by a factor
244	of two and can reach an order of magnitude. We estimated dead counts for each taxon by
245	assuming that a standard volume of 1 cm ³ was counted (and rounding to the nearest whole
246	individual). To facilitate direct comparison with our new dataset of modern salt-marsh
247	foraminifera we also standardized the taxonomy used by Scott et al. (1981), notably counts of
248	testate amoebae were removed and Trochammina macrescens was assigned to JmBp.
249	Trochammina inflata and Siphotrochammina lobata were merged (TiSl) in the combined dataset
250	since it is unclear if they were distinguished by Scott et al. (1981). Elevations in Scott et al.
251	(1981) were measured by levelling to a physical benchmark (which specific ones is unclear) with
252	a reported height relative to mean sea level (MSL) and these values are tabulated in the original
253	publication. However, Scott et al. (1981) provided a site-specific correction (+0.33 m at Tryon
254	and -0.30 m at Wolfe Inlet) to restate "benchmark MSL" relative to "tidal gauge MSL". We
255	apply this correction under the assumption that "tidal gauge MSL" adequately characterizes sea
256	level at the time of sample collection in 1978 CE. Conversion among tidal datums used the same
257	tide gauges as we employed for the samples collected in 2022. The counts and elevations
258	estimated from Scott et al. (1981) are tabulated in the supplementary information. Hierarchical
259	cluster analysis was performed using the <i>pheatmap</i> package for R (Raivo 2018).

- 260
- 261 3.4 Bulk sediment isotopic analysis

262 In preparation for isotopic analysis, bulk sediment was freeze dried and then milled to a fine,

263 homogenized powder. Samples were not acidified given the scarcity of carbonate that we

264 observed in modern PEI salt marshes. Sample analysis was performed on a commercial basis by

265	the Yale Analytical and Stable Isotope Center where carbon and nitrogen isotope abundances
266	were measured simultaneously on the same sample material and instrument (Thermo DeltaQ
267	with elemental analyser). Repeated measurement of internal standards indicates uncertainty of
268	$\pm 0.1\%$ for δ^{13} C and $\pm 0.2\%$ for δ^{15} N. The exception is one sample (Haldimand River, transect 1,
269	station 16) that was measured at the University of North Carolina Wilmington.

271 Carbon isotope ratios are expressed relative to the Vienna Pee Dee Belemnite standard ($\delta^{13}C$; ‰ 272 VPDB). In salt marshes along the Atlantic coast of North America, the principal source of 273 organic carbon to bulk sediment is from *in-situ* plants (Chmura and Aharon 1995). Today these 274 plants utilize atmospheric CO₂ that was enriched in ¹²C through combustion of fossil fuels (the 275 Suess effect; Keeling 1979). This process changed the isotopic composition of the atmosphere 276 from -6.4‰ in 1845 CE (Francey et al. 1999) to -8.6‰ in 2017 CE (at Mauna Loa; Keeling et 277 al. 2001). To facilitate comparison between carbon isotope ratios in modern and fossil bulk 278 sediment it is prudent to correct for the Suess effect (Wilson 2017). We added 2.06‰ to 279 measured δ^{13} C values, which is the average annual value in the decade preceding sample 280 collection (Kwon et al. 2022) and is likely to approximate the magnitude of time represented by 281 a surface sample. The adjusted values are referred to as $\delta^{13}C_{adj}$. Nitrogen isotope values are 282 expressed relative to the ratio of ¹⁴N and ¹⁵N in air (δ^{15} N; ‰ AIR).

283

4. Results

We collected a total of 143 samples, of which 99 contained at least 30 dead tests. There were 14taxa in these samples, of which nine/five exceeded a relative abundance of 5/10% in at least one

sample. The majority (91%) of individuals were *Miliammina fusca*, TiSl, or BpJm and only these taxa had a mean abundance greater than 6%. Given the limited influence of rare taxa on RSL reconstructions (Kemp et al. 2018; Walker et al. 2020), we focus on these three principal taxa in the text and figures. However, raw counts and elevation for all samples and taxa are provided in a supplementary file. In each modern sample we measured the concentration of total organic carbon (TOC) and total nitrogen (TN) and their isotopic composition (δ^{13} C and δ^{15} N). These results are tabulated in a supplementary file.

294

295 *4.1 Tryon*

296 Two transects established at Tryon extend from unvegetated creek beds with near-vertical and 297 slumping banks, across the salt-marsh platform that is vegetated by Spartina patens and 298 Distichlis spicata with patches of stunted Spartina alterniflora in depressions, and into a 299 soil-forming, supratidal zone of upland forest with Lupinus sp. (Figure 2). Samples below MTL 300 included BpJm with a mean abundance of 39% (range 7-59%). This assemblage likely reflects 301 the slumping of bank sediment to lower elevations and downward erosion of the tidal flat into 302 older, underlying high salt-marsh sediment. A lack of live tests prevents testing this hypothesis 303 by comparing live and dead assemblages. At 0-0.6 m MTL, Miliammina fusca has a mean 304 abundance of 51% (range 24-83%) across the two transects. From 0.65 m MTL to the highest 305 occurrence of foraminifera (at 1.03 m MTL), the mean abundance of BpJm was 50% (range 8-306 96%). Trochammina inflata is present across the vegetated marsh with a mean abundance of 307 21%.

308

309 The six samples collected below MTL at Tryon had a mean TOC composition of 3.2%, mean 310 $\delta^{13}C_{adj}$ of -18.4‰, and mean $\delta^{15}N$ of 2.7‰ (Figure 3). Samples from the Spartina alterniflora-311 dominated low marsh are characterized by mean TOC of 7.9%, mean $\delta^{13}C_{adj}$ of -17.2%, and 312 mean δ^{15} N of 6.0%. The high salt-marsh platform vegetated largely by *Spartina patens* and 313 Distichlis spicata yielded a mean TOC value of 11.4%, mean $\delta^{13}C_{adi}$ of -17.4%, and mean $\delta^{15}N$ 314 of 6.4‰. The similarity in carbon isotopic composition between samples below MTL and those 315 on the adjacent salt marsh further (beyond geomorphic observations) suggest that tidal flat at 316 Tryon likely receives a significant contribution of allochthonous carbon from slumping of creek 317 banks and remobilization of older high salt-marsh sediment through erosion. In contrast, the 318 nitrogen isotopic composition of samples below MTL is systematically less than from those on 319 the salt marsh. Bulk surface sediment from locations in the transitional marsh vegetated by 320 *Carex* sp. have elevated TOC (mean 22.7%), more negative $\delta^{13}C_{adj}$ values (mean -25.3%) and 321 lower $\delta^{15}N$ (mean 4.9‰) than the neighbouring salt marsh occupied by C₄ plants, but are similar in composition to sediment in the surrounding upland (mean TOC of 17.8%, $\delta^{13}C_{adj}$ of -26.9‰, 322 323 and δ^{15} N of 1.7‰).

324

325 *4.1.2 Augustine*

The first transect at Augustine extends from an unvegetated tidal flat of coarse sand, across a
high marsh zone of *Spartina patens* with *Distichlis spicata* and then a transitional zone of *Carex paleacea*, before ending in a forested upland (Figure 2). The concentration of foraminifera in the
sandy tidal-flat sediment was too low to generate a viable count. On the vegetated salt marsh, *Miliammina fusca* is most abundant in a depression, reaching 80% at 0.48 m MTL. From 0.6 m
MTL to the highest occurrence of foraminifera on transect 1 (at 0.85 m MTL), the most abundant

332 taxa were BpJm (mean 44%; range 29–58%) and T. inflata (mean 13%; range 8–26%). The 333 second transect at Augustine was positioned to sample a contrasting brackish, transitional zone 334 vegetated by Typha augustifolia rather than Carex paleacea (Figure 2). At locations vegetated by 335 Spartina patens and Distichlis spicata (0.57–0.73 m MTL), Miliammina fusca was the most 336 common taxa (mean 40%; range 20-74%). In the transitional zone (0.77 m MTL to the highest 337 occurrence of foraminifera at 1.00 m MTL), BpJm had a mean abundance of 76% (range 62– 338 88%). Despite differences in vegetation, both transects at Augustine display a similar pattern of 339 *Miliammina fusca* characterizing lower elevations (including depressions within the high marsh 340 where ponding likely occurs) and BpJm being more prevalent at higher elevations. However, the 341 highest occurrence of foraminifera is markedly higher on transect 2 than on transect 1, which 342 may reflect localized retention of tide water (the substrate in the *Typha augustifolia* zone on 343 transect 2 was notably wetter than in the corresponding zone of *Carex paleacea* on transect 1). 344 The highest occurrence of foraminifera at Augustine (1.00 m MTL) is consistent with Tryon 345 (1.03 m MTL); the difference between sites is smaller than the vertical spacing of samples 346 through transitional vegetation zones.

347

The tidal flat of coarse sand on transect 1 at Augustine is distinctive because it has low TOC (mean 0.42%) and mean $\delta^{13}C_{adj}$ of -11.8% (Figure 3), which may reflect some input from carbonate given the low organic content and lack of acidification during sample processing. These samples did not contain sufficient nitrogen to measure $\delta^{15}N$. Across the two transects samples in the high salt-marsh community of *Spartina patens* and *Distichlis spicata* are characterized by mean TOC of 21.9%, mean $\delta^{13}C_{adj}$ of -15.3%, and mean $\delta^{15}N$ of 6.2‰. The transition between high salt-marsh platform and the upland is occupied by either *Carex paleacea*

355 (transect 1) or *Typha augustifolia* (transect 2). These settings have similar organic content (mean 356 TOC of 31.4% and 29.6% respectively), but different stable isotopic composition. Three samples from the *Carex paleacea*-dominated transition had less negative $\delta^{13}C_{adi}$ values (mean -18.0%) 357 358 than the nine samples from the Typha augustifolia-dominated transition (mean -23.7%). This 359 pattern could reflect recent expansion of *Carex paleacea* into locations previously occupied by a 360 community of C₄ plants or mixing of carbon sources. The nitrogen isotopic composition of these 361 two botanical zones is similar (mean δ^{15} N of 1.5% in *Carex paleacea* and 1.6% in *Typha* 362 augustifolia). Upland sediment at Augustine has mean TOC of 29.6%, although this environment 363 on transect 1 was often characterized by higher TOC (three out of four samples exceeded 37%) 364 than transect 2 (8–30.7%). Similarly, the mean $\delta^{13}C_{adj}$ value (–24.9‰) includes two (of four) 365 samples on transect 1 with measured values less negative than -20.7%, while each of the five 366 upland samples on transect 2 were more negative than -26.1%. The mean bulk-sediment $\delta^{15}N$ 367 value for upland samples at Augustine is 1.6% and there is no notable difference between the 368 two transects.

369

370 *4.1.3 Wolfe Inlet*

The transect at Wolfe extended from a sandy tidal flat, across a pronounced step in elevation, to a salt-marsh platform vegetated by a mixed community of *Carex paleacea* with *Spartina patens*, into a brackish, transitional zone of *Typha augustifolia*, and ended in a densely thicketed supratidal upland (Figure 2). The salt-marsh platform at this site was irregular and we noted that the sediment surface often lay beneath a mat of fresh plant material. The step on this salt-marsh platform is erosive; therefore the three samples below MTL likely include a high proportion of allochthonous tests. At elevations from 0.61 m MTL to the highest occurrence of foraminifera at

378 0.83 m MTL, all samples were characterized by high abundances of BpJm (mean 74%; range 379 54–100%). Notably, the entire vegetated salt marsh on this (representative) transect exists more 380 than 0.3 m above MHHW, which is a large elevation in the context of a 0.71 m great diurnal tidal 381 range. Furthermore, much of the salt marsh is higher than the upland located further inland along 382 the transect, which further shows that the site has an unusual eco-geomorphology. The lack of 383 foraminifera in the samples vegetated by *Typha augustifolia* suggests that despite being lower 384 than much of the salt marsh it is not sufficiently inundated to sustain a population of 385 foraminifera.

386

387 Bulk sediment in the three samples below MTL is characterized by mean TOC of 3.2%, mean 388 $\delta^{13}C_{adi}$ value of -18.8‰, and mean $\delta^{15}N$ of 0.1‰ (Figure 3). The irregular platform vegetated by 389 *Carex paleacea* is represented by 16 samples that show a systematic change in TOC; the five 390 samples closest to the marsh front had mean TOC of 15.6%, compared to 26.1% for the other 11 391 samples collected further into the marsh and at higher elevation. There was no discernible 392 corresponding trend in $\delta^{13}C_{adj}$ values (mean –23.1‰) suggesting that while the amount of 393 organic input varied its source likely did not. Samples from the zone vegetated by Typha 394 *augustifolia* had relatively high organic content (mean TOC of 35.5%), but variable $\delta^{13}C_{adi}$ value 395 (mean of -18.9% but ranging from -16.2% to -22.1%). The three upland samples were 396 similarly rich in organic carbon (mean TOC of 38.9%) with variable $\delta^{13}C_{adj}$ values (-15.6%, -397 15.3‰, and –26.1‰). These measurements suggest that the upland and *Typha augustifolia* zones 398 at Wolfe Inlet include organic carbon with different sources on small spatial scales (meters). This 399 likely reflects the difficulty of locating a marsh sediment surface in these zones; TOC measured 400 on the samples (33.0–39.9%) is similar to the value for plants which suggests that little sediment

401 was included in the sample. The lack of sediment likely reflects erosion of the site as evidenced 402 by the irregular marsh surface with a retreating marsh front and extensive ponding. Notably, some of the samples had measured $\delta^{13}C_{adi}$ values that are typical of sediment with input of 403 404 organic carbon from C₄ plants (Lamb et al. 2006) despite there being few living C₄ plants at the 405 site in 2022 CE. However, Scott et al. (1981) described plant communities at Wolfe Inlet in 1978 406 CE with plentiful C₄ plants including a marsh platform dominated by *Spartina patens* and 407 transitional zone of Spartina cynosuroides. This change in vegetation suggests that surface 408 sediment samples could include organic carbon of mixed (C₃ and C₄ plants) sources either 409 through plant material redistributed by erosion or by sample thicknesses capturing the temporal 410 evolution of plant communities. Across the vegetated salt marsh at Wolfe Inlet there is little 411 variability in δ^{15} N values (means of 1.3‰, 1.9‰, and 2.0‰ in the *Carex paleacea*, *Typha* 412 augustifolia, and upland zones respectively).

413

414 *4.1.4 Haldimand River*

415 Two transects at Haldimand River extended from unvegetated tidal flats, across the vegetated 416 salt-marsh platform (Spartina patens and Distichlis spicata with occasional Juncus sp.) and up to 417 either side of an upland 'island' that is skirted by a narrow band of *Carex paleacea* (Figures 1 418 and 2). Although the transition from tidal flat to salt marsh is less pronounced at Haldimand 419 River than the other sites, we observed evidence of the platform edge being actively eroded (e.g., 420 sub-tidal sediment comprised disaggregated peat) at the time of sample collection. Therefore, the 421 relatively high abundances of BpJm (up to 64%) and T. inflata (up to 46%) in tidal-flat sediment, 422 likely reflect remobilization of older, high-marsh tests by erosion rather than an *in-situ* 423 assemblage. The distribution of foraminifera is similar on both transects. At 0-0.35 m MTL,

424	assemblages are co-dominated by BpJm (mean 44%; range 21-63%), Miliammina fusca (mean
425	27%; range 5–52%), and <i>T. inflata</i> (mean 24%; range7–46%). Above approximately MHHW
426	(0.38 m MTL at this site), there is a reduction in the abundance of Miliammina fusca (less than
427	9%), resulting in BpJm being the dominant species (mean 73%; range 54–86%). The highest
428	occurrence of foraminifera is at 0.65 m MTL on transect 1 and 0.62 m MTL on transect 2. This
429	difference is less than the vertical spacing of samples along the transects.
430	
431	Five samples collected below MTL on the unvegetated channel bottom are characterized by a
432	mean TOC of 8.8% and a mean $\delta^{13}C_{adj}$ value of -12.3% (Figure 3). One of these samples yielded
433	an anomalous δ^{15} N value of -3.3 ‰, while the remaining four were in the range 2.8–4.2‰.
434	Samples on the marsh at the edge of the channel vegetated by Spartina alterniflora had mean
435	TOC of 7.0% and a mean $\delta^{13}C_{adj}$ value of –13.4‰. The three samples had $\delta^{15}N$ values of 0.3–
436	0.8‰. Both transects include a broad high salt-marsh platform dominated by <i>Spartina patens</i> .
437	Samples from this botanical zone show a notable trend in TOC $\delta^{13}C_{adj}$ values. On transect 1 three
438	samples at 0.15–0.24 m MTL had TOC of 4.1–15.5% and $\delta^{13}C_{adj}$ values (–15.5% to –13.4‰)
439	that are typical of C_4 plants. In contrast, the four adjacent samples (0.33–0.44 m MTL) were
440	more organic (TOC of 14.6–25.1%) and yielded more negative $\delta^{13}C_{adj}$ values (–22.7‰ to –
441	19.0‰). On transect 2 samples at 0.17–0.33 m MTL had $\delta^{13}C_{adj}$ values of –14.1‰ to –12.9‰,
442	compared to two adjacent samples (0.37 and 0.62 m MTL) with the same surface vegetation, but
443	$\delta^{13}C_{adj}$ values of -24.7‰ and -24.3‰. This pattern could reflect recent colonization of higher
444	elevations by Spartina patens in response to RSL rise, with the result that 1-cm thick surface
445	samples capture an older botanical zone. In the Spartina patens zone the mean $\delta^{15}N$ value was

446	1.1‰ Samples from the zone of <i>Carex paleacea</i> have mean TOC of 8.4%, $\delta^{13}C_{adj}$ values (mean –
447	19.6‰) that straddle the ranges associated with C ₃ and C ₄ plants, and mean δ^{15} N of 3.0‰.

449 5. Discussion

450 *5.1 Relationship between elevation and inundation under different tidal regimes*

451 The relationship between sea-level proxies and tidal elevation is one of correlation rather than 452 direct causation (Gehrels, 2000). Vertical zonation of foraminiferal assemblages (and other 453 biological proxies such as plants) arises from the interaction of environmental variables, which 454 are themselves controlled principally by the balance between submergence and subaerial 455 exposure. Consequently, efforts to reconstruct RSL are underpinned by an assumption that 456 elevation adequately describes the gradient of inundation and, by extension, ecologically-457 significant environmental variables. Where efforts to document the modern distribution of sea-458 level proxies utilize data from multiple sites, it is common to express elevation as a standardized 459 water level index (SWLI) because the inundation characteristics at an absolute height (expressed 460 for example as m MTL) vary among sites with different tidal ranges (Horton and Edwards 2006; 461 Kemp et al. 2022). Gehrels (2000) termed this approach "height normalization" and it is widely 462 used for its simplicity in ensuring comparability of observations drawn from sites with differing 463 tidal ranges (Hawkes et al. 2010; Horton and Edwards 2006; Rush et al. 2021; Williams et al. 464 2021; Zong and Horton 1999). Less consideration has been given to differences in tidal regime 465 (diurnal, mixed, or semi-diurnal) because it rarely varies among sites in one study region.

466

Page 22 of 54

467	Our four study sites on PEI are unusual because they experience diurnal, mixed, and
468	semi-diurnal regimes. We evaluate the degree to which data from these four sites can (or cannot)
469	be combined into a unified training set by examining the relationship between salt-marsh
470	elevation (expressed as a SWLI) and inundation under different tidal regimes (Figure 4). For
471	three tide gauges in PEI, we predicted water levels at 15-minute intervals for 2018–2036 CE
472	using a tidal model. These predictions do not include non-astronomical (e.g., storms, prevailing
473	winds) forcing of water levels. The Victoria tide gauge has a semi-diurnal regime and is
474	appropriate for the Tryon and Augustine sites. The West Point tide gauge has a diurnal regime
475	and is located close to our study site at Wolfe Inlet. The Cape Egmont tide gauge has a mixed
476	regime and is located close to our study site at Haldimand River. At Victoria, the proportion of
477	time submerged during 2018–2036 CE at the elevation of MLW (SWLI=0) is 0.87, which
478	decreases to 0.52 at 0.5 SWLI (approximately MTL) and 0.09 at MHW (SWLI =1; Figure 4).
479	This relationship between elevation of predicted tides and flood duration is similar to tide gauges
480	on the U.S. Atlantic coast with semi-diurnal regimes (Kemp et al. 2022). At 43 tide gauge sites
481	between Florida and Maine (with median FF=0.20) the 95% confidence interval for flood
482	duration (during the 1983–2001 CE national tidal datum epoch) at MLW is 0.88–0.92, which is
483	slightly greater than Victoria. However, at elevations above ~ 0.6 SWLI the 50 th percentile of the
484	U.S. tide-gauge dataset is virtually indistinguishable from Victoria (Figure 4). This similarity in
485	the upper part of the intertidal zone is important because most RSL reconstructions target high
486	salt-marsh sediment, which indicates that expressing elevation as a SWLI captures its
487	relationship to flood duration even across a wide range of tidal ranges (0.30–5.87 m). We note
488	that this relationship is derived for predicted tides, but where great diurnal range is less than ~ 0.5
489	m actual flood durations can be markedly distorted by non-tidal water-level variability (Kemp et

490 al. 2022). However, where great diurnal tidal range is greater than ~ 1.0 m (e.g., Tryon and 491 Augustine) these non-tidal effects on inundation are relatively small over a 19-year epoch. In 492 contrast, the relationship between elevation and flood duration varies considerably among the 493 two locations with diurnal or mixed tidal regimes (West Point and Cape Egmont; Figure 4) and 494 compared to locations with semi-diurnal regimes such as Victoria and the U.S. Atlantic coast. 495 For example, the duration of inundation at MHW is two times greater at West Point (0.18) than 496 at Victoria (0.09) and at higher elevations the difference grows further to more than three times 497 (0.04 compared to 0.13 respectively at 1.09 SWLI). Similarly, the differences in flood duration 498 between Cape Egmont and West Point can be large (up to 0.08 at 0.58 SWLI). We propose that 499 use of a SWLI does not adequately capture the relationship between elevation and inundation 500 among sites with different tidal regimes.

501

502 Gehrels (2000) proposed an alternative approach ("flooding duration normalization") to SWLIs 503 where elevations are expressed as the proportion of time submerged by water (or inversely time 504 exposed to air), which was described as more ecologically plausible than height normalization 505 because flood duration (not elevation) exerts a first-order control on foraminifera and other 506 ecological variables. Transfer functions that employ a modern training set where elevation is 507 expressed as a flood duration will return estimates of time submerged, which is converted back 508 to an absolute height under an assumption that the relationship between flood duration and 509 elevation is unchanged through time (and therefore implicitly also assumes a stationary tidal 510 range). Gehrels (2000) evaluated this approach to normalization at four sites in Maine with a 511 shared (semi-diurnal) tidal regime and showed that the pattern of RSL change reconstructed was 512 the same as with height normalization, but that flooding duration normalization yielded smaller

uncertainties than height normalization. The flooding duration normalization approach could
facilitate combining modern datasets from our four sites in PEI. However, our remaining
discussion of sea-level proxies focuses primarily on a combined dataset of observations from the
semi-diurnal sites Tryon and Augustine because these sites preserve the thickest sequences of
salt-marsh sediment and the Wolfe Inlet site appears to be actively degrading and is unlikely in
equilibrium with modern sea level.

519

520 Space-for-time substitution dictates that the pronounced variability in tidal regime observed over 521 a relatively short distance of PEI's coastline today could be mirrored by shifts in regime through 522 time at a single site. Modelling indicate that the lunar, semi-diurnal (M2) tidal component can 523 decrease sharply when nearby ice streams retreat (Velay-Vitow et al. 2020), which would 524 increase the form factor (see section 2). However, ice volume changes of this magnitude do not 525 characterize the past \sim 5000 years, which is likely the maximum time period preserved in the 526 salt-marsh sedimentary record preserved beneath PEI salt marshes (Scott et al. 1981; Vacchi et 527 al. 2018). Therefore, tidal regimes are likely unchanged in PEI during the late Holocene, 528 although changes in tidal range are possible through evolving bathymetry, as they are at study 529 sites along the Altantic coast of North America (Hill et al. 2011). During the past ~7000 years 530 these changes in tidal range are estimated to have been modest (Griffiths and Hill 2015; Uehara 531 et al. 2006).

532

533 5.2 Distribution of modern salt-marsh foraminifera

534 The modern foraminifera from Tryon and Augustine were combined with results reported by

535 Scott et al. (1981) from an additional transect at Tryon (Figure 1E; see section 3.3). The 536 standardized and combined dataset includes 104 samples with a minimum count size of 30 dead 537 tests collected above MTL (Figure 5). Diversity is low with 60/79/89 of the samples being 538 comprised more than 90/80/70% BpJm, TiSl, or Miliammina fusca. Although low diversity is 539 influenced by the need to standardize taxonomy between studies by combining taxa (e.g., 540 Balticammina pseudomacrescens, Jadammina macrescens, and Trochammina macrescens into 541 BpJm), assemblages in nearby regions display similarly low diversity (Gehrels et al. 2020). 542 Elevations between approximately MHHW and the highest occurrence of foraminifera (at 1.03m 543 MTL; HOF) are dominated by BpJm (Figure 5a) and notably seven samples with almost mono-544 specific assemblages of BpJm occur close to HOF (Figure 5b). These assemblages are typical of 545 the upper reaches of salt marshes in Maritime Canada (Barnett et al. 2016; Kemp et al. 2017; 546 Patterson et al. 2004; Scott and Medioli 1980) and northern New England (Gehrels 1994; 547 Gehrels 2000; Kemp et al. 2024). The HOF corresponds to an inundation level of 1.0% (Figure 548 4), which mirrors results from Connecticut and North Carolina where for a semblages 549 were present to the elevation of 0.7% and 1.0% inundation respectively (Kemp et al. 2022; 550 Wright et al. 2011). Elevations below approximately MHW are characterized by assemblages 551 with high proportions of *Miliammina fusca* at both sites and along each transect. Along the 552 Atlantic coast of North America, this assemblage is consistently recognized in low marsh and 553 tidal flat sediment (Edwards and Wright 2015; Wright et al. 2011). These presence of these two 554 assemblages at both sites, on each transect and in two studies conducted more than 40 years apart 555 indicates a high degree of spatial replication in foraminiferal assemblages, and by extension that 556 transitions between these assemblages in core samples represent changes in paleomarsh elevation 557 (Figure 5b).

559	Cluster analysis recognizes an assemblage with high relative abundance of TiSl (Figure 5b). Of
560	the 18 samples in this group, 14 were from Tryon (on each of the three transects), while four
561	were from Augustine (three on transect 1 and one on transect 2). Similarly, Tiphotrocha
562	comprimata is more common at Tryon (mean 10%, up to 34%) than at Augustine (mean 1%, up
563	to 4%). These results indicate that assemblages of foraminifera can display among-site
564	variability even at small spatial scales. Efforts to quantify the relationship between foraminifera
565	and tidal elevation for reconstructing RSL aim to provide a modern training set with sufficient
566	diversity of assemblages to provide analogues for assemblages preserved in core sediment. The
567	modern distribution of foraminifera at Tryon and Augustine indicates that efforts to provide a
568	suite of modern analogue assemblages should aim to capture among- rather than within-site
569	variability.

570

571 5.3 Utility of carbon isotopes in bulk sediment to establish informative priors

572 During photosynthesis plants preferentially use ¹²CO₂ and discriminate against ¹³CO₂, resulting 573 in a strong fractionation of stable carbon isotopes between the atmosphere and plant tissue. The 574 degree of fractionation is more pronounced in plants using the C₃ photosynthetic pathway than it 575 is in C₄ plants. Consequently, C₃ plant tissue is characterized by δ^{13} C values of approximately – 576 32‰ to -22‰, while the tissue of C₄ plants is greater than approximately -18‰ (Lamb et al. 577 2006; Wilson et al. 2024). Along a large proportion of the North American Atlantic coast, C₄ 578 plants (Spartina alterniflora, Spartina patens, and Distichlis spicata) are native and dominate 579 high salt-marsh platforms below approximately MHHW (Eleuterius 1976; Sage et al. 1999; Scott 580 et al. 1981). Above MHHW is a botanical transition to brackish and terrestrial communities of C₃

581 plants. Since *in-situ* deposition of plant material is the principal source of organic carbon 582 accumulating on the salt-marsh surface, bulk sediment δ^{13} C values reflect the dominant plant 583 community (e.g., Chmura and Aharon 1995; Middleburg et al. 1997; Tanner et al. 2010). Post-584 depositional changes to bulk-sediment δ^{13} C values are smaller than the difference between 585 modern depositional environments dominated by C₃ and C₄ plants (Benner et al. 1991; Benner et 586 al. 1987; Fogel et al. 1989; Gebrehiwet et al. 2008; Johnson et al. 2007). Consequently, bulk-587 sediment δ^{13} C values have been used to differentiate between sediment that likely formed above 588 or below MHHW and to constrain RSL reconstructions by providing an informative prior for 589 Bayesian transfer functions (Cahill et al. 2016; Stearns et al. 2023). Threshold δ^{13} C values for 590 identifying botanical (and subsequently elevation) zones requires a modern dataset of sediment 591 samples that are likely to be analogous to those in core material.

592

593 We standardized measurements of bulk surface sediment δ^{13} C values from salt marshes in 594 Delaware (see Kemp et al. 2024), southern New Jersey (Kemp et al. 2012), northern New Jersey 595 (Walker et al. 2021), Rhode Island (Stearns et al. 2023), Massachusetts (Kemp et al. 2024), and 596 PEI (this study). Since sampling spanned almost 15 years, measured δ^{13} C values were adjusted 597 for the Suess effect (mean annual values from Kwon et al. 2022), while sample elevations were 598 expressed relative to MHHW calculated from water levels measured at nearby tide gauges and 599 converted to a SWLI (MHHW=1 and MLLW=0) because tidal range varies among the study 600 areas. Samples from Wolfe Inlet and Haldimand River were excluded because they have diurnal 601 and mixed tidal regimes respectively (see section 5.1); all other sites have a semi-diurnal regime. 602 Adjustments for the Suess effect and tidal elevation used observations from the ten years 603 preceding sample collection since this window likely approximates the amount of time

604represented by a 1-cm thick surface sediment sample. The resulting dataset includes 301605observations (Figure 6). In previous studies (e.g., Kemp et al. 2024) the MHHW datum was606adopted as an elevation threshold between the high salt-marsh platform (with a cut-off value of607less negative than -17%) and adjacent brackish transitional zone (samples more negative than a608cut-off value set at -20%, but with foraminifera present).

609

610 In the newly compiled dataset, there are 108 samples with δ^{13} C values more negative than – 611 20.0%, of which 84 (78%) lie above MHHW, while 148 (93%) of the samples less negative than 612 -17.0% accumulated below MHHW (Figure 6). This pattern is consistent across the study sites 613 from Delaware to PEI, which suggests that choices of threshold height and $\delta^{13}C$ cut-off values 614 are likely unchanged through the late Holocene in response to (for example) climate variability, 615 including salinity changes from drought (Malamud-Roam and Ingram 2004). The coast line from 616 Delaware to the Canadian Maritimes is likely the spatial limit of adopting this approach because 617 salt marshes further south (Eleuterius 1976) and north (Gehrels et al. 2020) are more commonly 618 vegetated by C₃ grasses, which serves to remove the isoptic contrast between intertidal and 619 supratidal environments (Kemp et al. 2017). We explored how adopting alternative thresholds 620 and cut-off values might improve confidence in recognizing elevation zones within salt marshes 621 that are subsequently employed as informative priors in BTFs (Figure 7). For the lower boundary 622 of the brackish transitional zone, the proportion of samples being accurately assigned increases 623 to ≥ 0.95 by lowering the elevation threshold from 1 SWLI (i.e., MHHW) to 0.93 SWLI (i.e., 624 0.12 m below MHHW at Tryon and Augustine), or by adjusting the δ^{13} C cut-off value from – 625 20.0% to -24.5%. Smaller changes are needed to increase confidence in recognizing the upper 626 limit of the high salt-marsh platform to ≥ 0.95 . Increasing the elevation threshold from 1 SWLI

(i.e., MHHW) to 1.04 SWLI (i.e., 0.07 m above MHHW at Tryon and Augustine) increases
confidence to 0.956. Adjusting the cut-off value from –17.0‰, while maintaining the MHHW
threshold does not markedly increase confidence. Figure 7 shows that in both cases the
contoured confidence levels parallel (approximately) the x-axis representing cut-off values,
which suggests that a smaller/larger change to the elevation threshold/cut-off values would be
necessary to improve confidence.

633

634 Adopting bulk-sediment δ^{13} C values as informative priors for BTFs does not require that the 635 threshold elevation be a singular plane between adjacent and vertically-discrete ecological zones. 636 The BTF of Cahill et al. (2016) does not treat informative priors as hard bounds on paleomarsh 637 elevation reconstructions. For example, in a core of salt-marsh sediment at Leeds Point in New 638 Jersey (Cahill et al. 2016), δ^{13} C values in 18 basal samples indicated accumulation above 639 MHHW. Paleomarsh elevations reconstructed by a BTF without informative priors reached 640 above MHHW for 17 of the samples, while reconstructions for all samples included MHHW 641 when informative priors were introduced. We propose that the MHHW threshold be revised 642 slightly upward for the high salt-marsh platform and slightly downward for the brackish 643 transitional zone. At Tryon and Augustine this would result in a ~ 0.19 m overlap (0.93–1.04 644 SWLI) between zones of C_3 and C_4 plants. This gradational relationship is ecologically 645 reasonable and may represent micro-scale differences in inundation regime, post-mortem mixing 646 of plant litter, surviving stands of C₄ plants despite RSL rise leaving them below MHHW, or the 647 ten-year period used to adjust measured δ^{13} C values and elevations being an imperfect time 648 window for ecological response and representing sample thickness.

649

Page 30 of 54

650 *5.4 Nitrogen isotopes in bulk sediment as sea-level proxies*

651 The utility of stable carbon isotopes as sea-level proxies (section 5.3) is premised on recognizing 652 discrete botanical zones (or the boundary between them) rather than a statistical relationship 653 between δ^{13} C values and tidal elevation (Wilson et al. 2024). Other isotope systems could 654 similarly be employed to reconstruct paleomarsh elevation by identifying sediment that formed 655 in coastal environments with observable relationships to tidal datums. We evaluated the possible 656 use of nitrogen isotopes as a sea-level proxy because salt-marsh plants are widely reported to 657 have elevated $\delta^{15}N$ values. For example, measurements on *Spartina alterniflora* tissue yielded 658 high δ^{15} N values (6.0 ± 2.1‰ in the southeast United States and 3.8 ± 2.6‰ in the northeast 659 United States) compared to adjacent upland plants $(0.4 \pm 0.9\% \text{ and } -0.6 \pm 1.2\%, \text{ respectively})$ 660 (Peterson and Howarth 1987; Peterson et al. 1985). A more recent compilation of measurements 661 from *Spartina alterniflora* estimated δ^{15} N of 6.16 ± 0.14‰ from 316 samples distributed from 662 the Gulf of Mexico to the Canadian Maritimes in North America and sites in China (Zhang et al. 663 2024). These results suggest that δ^{15} N values may have utility in differentiating between samples 664 that formed in a salt marsh, or in a supra-tidal upland if the nitrogen isotopic composition of bulk 665 sediment reflects the dominant vegetation and is preserved in buried sediment.

666



668 marsh communities of Spartina patens and Distichlis spicata had slightly higher bulk-sediment

 δ^{15} N values (mean 6.2‰, standard deviation 0.97‰, n=30; Figure 6b) than the brackish,

670 transitional zones characterized by *Carex paleacea* and *Typha augustifolia* (mean 5.1‰,

671 standard deviation 1.8‰, n=22). The adjacent uplands however, had markedly lower δ^{15} N values

672 (mean 1.7‰, standard deviation 1.0‰, n=18). Surface data collected along two transects at Belle

673 Isle, Massachusetts display a very similar pattern to the results from PEI (Kemp et al. 2024; 674 Figure 6b). At Belle Isle mean δ^{15} N values were 6.9‰ for samples on the salt-marsh platform, 675 compared to 2.1‰ in samples of *Phragmites australis* with forbes (such as *Limonium nashi* and 676 Solidago sempervirens) collected above the highest occurrence of foraminifera. These results 677 suggest that surface bulk-sediment δ^{15} N values reflect the overlying vegetation and therefore 678 may have utility as a sea-level proxy by differentiating upland sediment that formed above the 679 influence of tides from sediment that accumulated on a salt marsh or transitional brackish zone 680 with a relationship to tidal datums. The difference between salt-marsh and upland plant δ^{15} N 681 values persists across a wide geographic range of sites (Cloern et al. 2002; Peterson et al. 1985), 682 which suggests that bulk-sediment δ^{15} N values may have correspondingly widespread utility as a 683 sea-level indicator. This contrasts with bulk-sediment δ^{13} C values that are most useful in the 684 limited geographic region in eastern North America where salt marshes are natively occupied by 685 C₄ plants (Wilson et al. 2024).

686

687 Employing bulk-sediment $\delta^{15}N$ values as a sea-level indicator requires that surface sediment 688 samples be analogues for their counterparts preserved in the sedimentary record. Sediment cores 689 from salt marshes in New Jersey (Velinsky et al. 2017) and New York City (Peteet et al. 2018) 690 show elevated δ^{15} N values in surface and shallow sediment (approximately 6–8‰) that decrease 691 downcore (abruptly in some cases) and stabilize at low values ($\sim 2\%$). This change is not 692 accompanied by an inference that salt-marsh sediment overlies upland sediment, in which case 693 the trend would be interpreted as a change in depositional environment. Rather the trend may 694 reflect either a change in the source of nitrogen, or post-depositional fractionation of nitrogen 695 isotopes during burial of sediment under increasingly anoxic conditions. The downcore trend in

696 δ^{15} N values in New Jersey and New York City was interpreted as a change in nitrogen source 697 caused by release of wastewater from nearby treatment plants or run-off of agricultural fertilizer 698 (Church et al. 2006; Peteet et al. 2018; Velinsky et al. 2017). This interpretation is supported by 699 a change through time from positive to negative correlation between $\delta^{15}N$ and total nitrogen 700 values (Peteet et al. 2018). PEI has a small population (\sim 160,000) of which approximately half 701 are serviced by central wastewater systems, therefore the discharge of treated water with high 702 δ^{15} N values is likely modest (compared for example to New York City), although modern δ^{15} N 703 values could be influenced by agricultural runoff (Jiang et al. 2015). If temporal δ^{15} N trends in 704 salt-marsh sediment are the result of historic increases in wastewater treatment and agricultural 705 runoff then δ^{15} N values measured in surface sediment may not be appropriate analogues for 706 older, downcore sediment. To some degree this is also the case for δ^{13} C values which are 707 corrected for the Suess effect (section 3.4), although any correction to $\delta^{15}N$ values would likely 708 have considerable spatial variability and is currently unquantified, which prevents use of $\delta^{15}N$ 709 values as a sea-level proxy. Furthermore, if modern salt-marsh values have artificially high $\delta^{15}N$ 710 because of human activities, then corrected values are likely to obscure the difference between 711 salt marsh and upland sediment.

712

Alternatively, downcore reduction of δ^{15} N values in salt-marsh stratigraphies may be caused by post-depositional change during burial under anoxic conditions, with the consequence that upland and salt-marsh environments have convergent δ^{15} N values and cannot be readily distinguished. The compiled data presented by Zhang et al. (2024) suggests that *Spartina alterniflora* tissue experiences a rapid post-mortem reduction in δ^{15} N (δ^{13} C values were unchanged). Living specimens had δ^{15} N of 6.55 ± 2.23‰ (n=272) compared to 2.76 ± 2.72‰

719 (n=29) for dead stands. The direction of this change suggests that differentiating salt-marsh and 720 upland environments may be become more difficult after deposition, although the surface bulk-721 sediment values we measured likely reflect input from dead plants and therefore capture short-722 term post-mortem changes in tissue isotopic composition. The cause of elevated δ^{15} N values in 723 salt-marsh plants is poorly understood, but Guiry et al. (2021) proposed that coupled 724 nitrification-denitrification by microbes causes high δ^{15} N in surface and shallow salt-marsh 725 sediment. Specifically, they propose that downward transport of oxygen by the roots of salt-726 marsh plants to depths that would otherwise be anoxic (due to saturation by tidal inundation and 727 the poorly drained nature of fine-grained sediment with relatively high organic content) creates 728 conditions conducive to coupled nitrification-denitrification. As sediment is buried below the 729 rhizosphere it becomes anoxic and the remaining nitrogen is subject to microbial activity which 730 may reduce δ^{15} N values (Gälman et al. 2009). In PEI, site geomorphology (slumping and erosive 731 creek banks), for a ninifera, and δ^{13} C values support the interpretation that surface sediment 732 collected below MTL on the tidal flat includes older high-marsh sediment. Notably this sediment has lower δ^{15} N values (mean 2.7%; Figure 6b), than surface sediment on the adjacent C₄ salt 733 734 marsh (mean 6.2%). This pattern is consistent with $\delta^{15}N$ values in older sediment having been 735 systematically lowered by post-depositional fractionation. Consequently, differences in bulk-736 sediment $\delta^{15}N$ values between botanical zones that are readily-identifiable in modern sediment 737 are erased during burial, which diminishes the utility of nitrogen isotopes as a sea-level proxy. 738

739 6. Conclusions

An early step in reconstructing relative sea level (RSL) from buried salt-marsh sediment ischaracterizing the modern, observable relationship between potential sea-level proxies and tidal

742	elevation. We collected 143 surface sediment samples along seven transects at four salt marshes
743	in Prince Edward Island (PEI) to generate a modern training set of foraminifera and bulk-
744	sediment isotopic ($\delta^{13}C_{adj}$ and $\delta^{15}N$) values. The four sites are unusual because they include
745	semi-diurnal tidal regimes (at Tryon and Augustine), a diurnal regime at Wolfe Inlet and a mixed
746	regime at Haldimand River despite their geographic proximity to one another. While sites with
747	different tidal ranges can be combined by standardizing elevation, this approach does not
748	accurately characterize the duration of tidal inundation among sites with different tidal regimes.
749	An approach of standardizing by flood duration could be used to combine sites with differing
750	tidal regimes. We therefore focused principally on results from the semi-diurnal sites.
751	Foraminifera on PEI salt marshes form low-diversity assemblages that have similar relationships
752	to tidal elevation to other regions on the Atlantic coast of North America. By sampling more than
753	one transect at each site and combining our results with those from Scott et al. (1981), we show
754	that assemblages are replicated within and among sites over more than 40 years. This regional-
755	scale training set captures inter-site variability and is appropriate for reconstructing relative sea
756	level. Bulk-sediment $\delta^{13}C_{adj}$ values reflect the dominant vegetation on the marsh surface and
757	differentiate readily between the salt-marsh platform occupied by C ₄ plants (below
758	approximately mean higher high water, MHHW) and the transitional salt marsh and surrounding
759	upland environments where C ₃ plants are dominant (above approximately MHHW). After
760	combining the new measurements from PEI with similar datasets from Delaware to
761	Massachusetts we explored the sensitivity of threshold elevations and cut-off $\delta^{13}C_{adj}$ values. We
762	propose that the zone of C_4 plants is recognized by $\delta^{13}C_{adj}$ values less negative than -17.0% and
763	extends to slightly above MHHW, while the zone of C_3 plants is recognized by $\delta^{13}C_{adj}$ values
764	more negative than –20.0‰ and extends slightly below MHHW. Bulk sediment $\delta^{15}N$ are

765	elevated in salt-marsh sediment compared to nearby upland sediment, but there is evidence that
766	post-depositional modification of nitrogen isotopes during burial under increasingly anoxic
767	conditions is likely to render the groups indistinguishable and prevent use of $\delta^{15}N$ as a sea-level
768	proxy.
769	
770	Acknowledgments
771	We thank Chrisopher Piecuch, Maeve Upton, and Kelly McKeon for their help in the field. We
772	thank editor Brendan Murphy, associate editor Nikole Bingham-Koslowski and two anonymous
773	reviewers for sharing their time and expertise to provide
774	
775	Funding
776	This work is supported by a CAREER award from the U.S. National Science Foundation (OCE-
777	1942563) to Kemp and by the Marine Institute under the Marine Research Programme funded by
778	the Irish Government (A4 project, Grant-Aid Agreement No. PBA/CC/18/01) to Edwards.
779	
780	Data Availability

781 All data are made available as a tabulated supporting file.

782 Figure Captions

- 783 Figure 1: (A,B) Location of study sites on Prince Edward Island (PEI), Canada. Location of 784 amphidromic points discussed in text are shown. Surface sediment samples were collected from 785 four salt marshes (C–F) in June 2022 to build a multi-proxy modern training set for 786 reconstructing relative sea level. Locations of tide gauges and sites used by Scott et al. (1981) to 787 describe the modern distribution of foraminifera are shown. NFLD = Newfoundland. 788 Coordinates are expressed in decimal degrees of latitude and longitude. 789 790 Figure 2: Relative abundance of foraminifera (limited to three key taxa: Balticammina 791 pseudomacrescens + Jadammina macrescens, Trochammina inflata, and Miliammina fusca) in 792 seven modern transects collected at four sites in Prince Edward Island, Canada. Tidal regime and 793 tidal range vary among sites, therefore absolute elevations should not be compared directly 794 among panels from different sites. Samples lacking foraminifera are denoted by shaded region. 795 MHHW = local mean higher high water. Note that y-axes (elevation and foraminiferal 796 abundance) scales are standardized for each study site but vary among sites. The single sample 797 marking the highest occurrence of foraminifera (HOF) on each transect is highlighted by a 798 heavier margin and labelled.
- 799

Figure 3: Bulk-sediment geochemistry measured in samples collected along seven modern
transects collected at four sites in Prince Edward Island, Canada. Tidal regime and tidal range
vary among some sites. MHHW = local mean higher high water, HOF = highest occurrence of
foraminifera (at Tryon and Augustine).

805	Figure 4: (A) Relationship between tidal elevation and flood duration at three tide-gauge sites in
806	Prince Edward Island Canada. Predictions of astronomical tides were generated by using a tidal
807	model for 2018–2036 CE at 15-minute intervals. Since tidal range varies among sites, elevation
808	is expressed as a standardized water level index (SWLI) where a value of 1 corresponds to local
809	mean high water (MHW) and a value of 0 to local mean low water (MLW). Flood duration is the
810	proportion of time during the 19-year tidal epoch that elevations are predicted to be submerged
811	by astronomical tides. For comparison, the relationship between elevation of predicted tides and
812	flood duration (1983–2001 CE) is shown for 43 tide gauges on the U.S. Atlantic Coast with
813	semi-diurnal tides and great diurnal tidal ranges from 0.30 m to 5.87 m. (B) Difference in the
814	duration of flooding at intervals of 0.01 SWLI between Victoria and the other locations.
815	Positive/negative values indicate that Victoria experiences longer/shorter submergence by tides.
816	(C) Difference in the elevation of flooding at intervals of 0.01 duration over the 19-year tidal
817	epoch between Victoria and the other locations. Positive/negative values indicate that the
818	elevation of a particular flood duration is lower/higher at Victoria.
819	
820	Figure 5: Distribution of salt-marsh foraminifera at sites with semi-diurnal tidal regime (Tryon

and Augustine) in Prince Edward Island. The standardized dataset uses four transects from the

822 study (collected in 2022 CE) and a transect collected at Tryon in 1978 CE by Scott et al. (1981).

823 (A) Relationship between assemblages of foraminifera and elevation. Only samples with dead

824 count exceeding 30 individuals and above mean tide level (MTL) are shown. (B) Cluster analysis

825 of the 104 samples constituting the modern training set. Four principal assemblages are identified

by bold outline.

828	Figure 6: (A) Compilation of bulk-sediment δ^{13} C values from six study areas (symbol shape and
829	fill) along the Atlantic coast of North America where high salt-marsh platforms are vegetated by
830	plants using the C ₄ photosynthetic pathway. For each dataset, measured $\delta^{13}C$ values were
831	adjusted for the Suess effect using the observed change in atmospheric $\delta^{13}C$ during the ten years
832	prior to sample collection. Sample elevation is expressed relative to tidal datums calculated using
833	measurements from nearby tide gauges during the ten years preceding sample collection. For
834	Prince Edward Island, data from Wolfe Inlet and Haldimand River are excluded since they have
835	diurnal and mixed tidal regimes respectively. The remaining data (Tryon and Augustine in Prince
836	Edward Island) all have semi-diurnal tidal regimes, but different tidal ranges. Therefore,
837	elevation is expressed as a standardized water level index (SWLI) where a value of 1
838	corresponds to local mean higher high water (MHHW) and a value of 0 represents mean lower
839	low water; HOF is the highest occurrence of foraminifera at Tryon or Augustine. Vertical dashed
840	lines represent the thresholds (-20% and -17%) that have typically been used to differentiate
841	samples that likely accumulated above and below the MHHW datum. Shaded regions
842	represented proposed updates to threshold values. (B) Bulk-sediment $\delta^{15}N$ values from two study
843	areas (δ^{15} N was not measured or reported for the other four study areas).
844	

Figure 7: Exploration of threshold δ^{13} C values for establishing if a sample likely accumulated in the brackish transitional zone (top panel) or on the high salt-marsh platform (lower panel). Observational data are the results from six regions along the Atlantic coast of North America with semi-diurnal tidal regimes but different tidal ranges. Therefore, elevation is expressed as a standardized water level index (SWLI), where a value of 1 corresponds to local mean higher high

- 850 water (MHHW) and a value of 0 is local mean tide level. The original thresholds used values
- 851 more negative than -20% to identify samples that accumulated above MHHW and less negative
- than -17‰ to characterize samples that formed below MHHW. Cell shading represents the
- 853 proportion of observations (samples) that are assigned to the environment of deposition for
- 854 combinations of elevation and δ^{13} C thresholds (contours for 0.75, 0.85, and 0.95 are shown and
- labelled). Alternative thresholds can be set by adjusting the elevation away from MHHW and/or
- 856 by selecting different δ^{13} C values (red arrows and symbols).

857 Competing Interests

- 858 The authors declare there are no competing interests.
- 859

860 References

- Anisfeld, S.C., Kemp, A.C., and O'Connell, J. 2019. Salt marsh migration into lawns revealed by
 a novel sediment-based approach. Estuaries and Coasts, 42: 1419-1429.
 doi:https://doi.org/10.1007/s12237-019-00590-6.
- Argow, B.A., Hughes, Z.J., and FitzGerald, D.M. 2011. Ice raft formation, sediment load, and
 theoretical potential for ice-rafted sediment influx on northern coastal wetlands.
 Continental Shelf Research, 31: 1294-1305. doi:https://doi.org/10.1016/j.csr.2011.05.004.
- Barnett, R.L., Garneau, M., and Bernatchez, P. 2016. Salt-marsh sea-level indicators and transfer
 function development for the Magdalen Islands in the Gulf of St. Lawrence, Canada.
 Marine Micropaleontology, 122: 13-26.
 doi:http://dx.doi.org/10.1016/j.marmicro.2015.11.003.
- Benner, R., Fogel, M.L., and Sprague, E.K. 1991. Diagenesis of belowground biomass of
 Spartina alterniflora in salt-marsh sediments. Limnology and Oceanography, 36: 1358 1374. doi:https://doi.org/10.4319/lo.1991.36.7.1358.
- Benner, R., Fogel, M.L., Sprague, E.K., and Hodson, R.E. 1987. Depletion of ¹³C in lignin and its implications for stable isotope studies. Nature, **329**: 708-710. doi:https://doi.org/10.1038/329708a0.
- Bertness, M.D. 1991. Zonation of *Spartina patens* and *Spartina alterniflora* in New England salt
 marsh. Ecology, 72: 138-148. doi:https://doi.org/10.2307/1938909.
- Britton, K., Müldner, G., and Bell, M. 2008. Stable isotope evidence for salt-marsh grazing in the
 Bronze Age Severn Estuary, UK: implications for palaeodietary analysis at coastal sites.
 Journal of Archaeological Science, 35: 2111-2118.
 doi:https://doi.org/10.1016/j.jas.2008.01.012.
- Cahill, N., Kemp, A.C., Parnell, A.C., and Horton, B.P. 2016. A Bayesian hierarchical model for reconstructing relative sea level: from raw data to rates. Climate of the Past, 12: 525-542.
 doi:https://doi.org/10.5194/cp-12-525-2016.
- Chmura, G.L., and Aharon, P. 1995. Stable carbon isotope signatures of sedimentary carbon in coastal wetlands as indicators of salinity regime. Journal of Coastal Research, 11: 124-135.
- Church, T.M., Sommerfield, C.K., Velinsky, D.J., Point, D., Benoit, C., Amouroux, D., Plaa, D.,
 and Donard, O.F.X. 2006. Marsh sediments as records of sedimentation, eutrophication
 and metal pollution in the urban Delaware Estuary. Marine Chemistry, 102: 72-95.
 doi:https://doi.org/10.1016/j.marchem.2005.10.026.

893 894 895	Cloern, J.E., Canuel, E.A., and Harris, D. 2002. Stable carbon and nitrogen isotope composition of aquatic and terrestrial plants of the San Francisco Bay estuarine system. Limnology and Oceanography, 47 : 713. doi:https://doi.org/10.4319/lo.2002.47.3.0713.
896 897 898	Edwards, R.J., and Wright, A.J. 2015. Foraminifera. <i>In</i> Handbook of Sea-Level Research. <i>Edited by</i> I. Shennan and A.J. Long and B.P. Horton. John Wiley & Sons, Chichester. pp. 191-217.
899 900	Eleuterius, L. 1976. The distribution of <i>Juncus roemerianus</i> in the salt marshes of North America. Chesapeake Science, 17 : 289-292. doi:https://doi.org/10.2307/1350516.
901 902 903	Ember, L.M., Williams, D.F., and Morris, J.T. 1987. Processes that influence carbon isotope variations in salt marsh sediments. Marine Ecology Progress Series, 36: 33-42. doi:https://doi.org/10.3354/meps036033.
904 905 906	Engelhart, S.E., and Horton, B.P. 2012. Holocene sea level database for the Atlantic coast of the United States. Quaternary Science Reviews, 54 : 12-25. doi:https://doi.org/10.1016/j.quascirev.2011.09.013.
907 908 909 910 911	Filipescu, S., and Kaminski, M.A. Re-discovering <i>Entzia</i> , an agglutinated foraminifer from the Transylvanian salt marshes. <i>In</i> Eigth International Workshop on Agglutinated Foraminifera. Cluj-Napoca, Romania 2008. <i>Edited by</i> S. Filipescu and M.A. Kaminski. The Grzybowski Foundation. Vol. Grzybowski Foundation Special Publication No. 16, pp. 29-35.
912 913 914	FitzGerald, D.M., Hughes, Z.J., Georgiou, I.Y., Black, S., and Novak, A. 2020. Enhanced, climate-driven sedimentation on salt marshes. Geophysical Research Letters, 47 : e2019GL086737. doi:https://doi.org/10.1029/2019GL086737.
915 916 917	Fogel, M.L., Kent Sprague, E., Gize, A.P., and Frey, R.W. 1989. Diagenesis of organic matter in Georgia salt marshes. Estuarine, Coastal and Shelf Science, 28: 211-230. doi:https://doi.org/10.1016/0272-7714(89)90067-X.
918 919 920 921	Francey, R., Allison, C., Etheridge, D., Trudinger, C., Enting, I., Leuenberger, M., Langenfelds, R., Michel, E., and Steele, L. 1999. A 1000-year high precision record of δ ¹³ C in atmospheric CO ₂ . Tellus B, 51 : 170-193. doi:https://doi.org/10.1034/j.1600- 0889.1999.t01-1-00005.x.
922 923 924	Gälman, V., Rydberg, J., and Bigler, C. 2009. Decadal diagenetic effects on δ ¹³ C and δ ¹⁵ N studied in varved lake sediment. Limnology and Oceanography, 54 : 917-924. doi:https://doi.org/10.4319/lo.2009.54.3.0917.
925 926 927 928	Garrett, E., Gehrels, W.R., Hayward, B.W., Newnham, R., Gehrels, M.J., Morey, C.J., and Dangendorf, S. 2022. Drivers of 20th century sea-level change in southern New Zealand determined from proxy and instrumental records. Journal of Quaternary Science. doi:https://doi.org/10.1002/jqs.3418.

929 Gebrehiwet, T., Koretsky, C.M., and Krishnamurthy, R.V. 2008. Influence of Spartina and 930 Juncus on saltmarsh sediments III; organic geochemistry. Chemical Geology, 255: 114-931 119. doi:https://doi.org/10.1016/j.chemgeo.2008.06.015. 932 Gehrels, W.R. 1994. Determining relative sea-level change from salt-marsh foraminifera and 933 plant zones on the coast of Maine, U.S.A. Journal of Coastal Research, 10: 990-1009. 934 Gehrels, W.R. 2000. Using foraminiferal transfer functions to produce high-resolution sea-level 935 records from salt-marsh deposits, Maine, USA. The Holocene, 10: 367-376. 936 doi:https://doi.org/10.1191/095968300670746884. 937 Gehrels, W.R., Dangendorf, S., Barlow, N., Saher, M., Long, A., Woodworth, P., Piecuch, C., 938 and Berk, K. 2020. A preindustrial sea-level rise hotspot along the Atlantic coast of North 939 America. Geophysical Research Letters, 47: e2019GL085814. 940 doi:https://doi.org/10.1029/2019GL085814. 941 Griffiths, S.D., and Hill, D.F. 2015. Tidal Modeling. In Handbook of Sea-Level Research. Edited by I. Shennan and A.J. Long and B.P. Horton. John Wiley and Sons. pp. 438-451. 942 943 Guiry, E., Noël, S., and Fowler, J. 2021. Archaeological herbivore δ^{13} C and δ^{34} S provide a 944 marker for saltmarsh use and new insights into the process of ¹⁵N-enrichment in coastal 945 plants. Journal of Archaeological Science, 125: 105295. 946 doi:https://doi.org/10.1016/j.jas.2020.105295. 947 Hawkes, A.D., Horton, B.P., Nelson, A.R., and Hill, D.F. 2010. The application of intertidal 948 foraminifera to reconstruct coastal subsidence during the giant Cascadia earthquake of 949 AD 1700 in Oregon, USA. Quaternary International, 221: 116-140. 950 doi:https://doi.org/10.1016/j.quaint.2009.09.019. 951 Hill, D.F., Griffiths, S.D., Peltier, W.R., Horton, B.P., and Tornqvist, T.E. 2011. High-resolution 952 numerical modeling of tides in the western Atlantic, Gulf of Mexico, and Caribbean Sea 953 during the Holocene. Journal of Geophysical Research, 116: C10014. 954 doi:https://doi.org/10.1029/2010JC006896. 955 Horton, B.P., and Edwards, R.J. 2006. Quantifying Holocene sea-level change using intertidal 956 foraminifera: lessons from the British Isles. Cushman Foundation for Foraminiferal 957 Research, Special Publication, Cushman Foundation for Foraminiferal Research, 958 Washington D.C. 959 Jiang, Y., Nishimura, P., van den Heuvel, M.R., MacQuarrie, K.T.B., Crane, C.S., Xing, Z., 960 Raymond, B.G., and Thompson, B.L. 2015. Modeling land-based nitrogen loads from 961 groundwater-dominated agricultural watersheds to estuaries to inform nutrient reduction 962 planning. Journal of Hydrology, 529: 213-230. 963 doi:https://doi.org/10.1016/j.jhydrol.2015.07.033. 964 Johnson, B.J., Moore, K.A., Lehmann, C., Bohlen, C., and Brown, T.A. 2007. Middle to late 965 Holocene fluctuations of C₃ and C₄ vegetation in a northern New England salt marsh,

966 967	Sprague Marsh, Phippsburg Maine. Organic Geochemistry, 38 : 394-403. doi:https://doi.org/10.1016/j.orggeochem.2006.06.006.
968	Johnson, D.S., and York, H.H. 1915. The relation of plants to tide-levels; a study of factors
969	affecting the distribution of marine plants. Botanical contribution from the Johns Hopkins
970	University. Carnegie Institution of Washington, Washington, D.C.
971	Keeling, C.D. 1979. The Suess effect: ¹³ Carbon- ¹⁴ Carbon interrelations. Environment
972	International, 2: 229-300. doi:https://doi.org/10.1016/0160-4120(79)90005-9.
973	Keeling, C.D., Piper, S.C., Bacastow, R.B., Wahlen, M., Whorf, T.P., Heimann, M., and Meijer,
974	H.A. 2001. Exchanges of atmospheric CO ₂ and ¹³ CO ₂ with the terrestrial biosphere and
975	oceans from 1978 to 2000. I. Global aspects. Scripps Institution of Oceanography.
976	Kemp, A.C., and Telford, R.J. 2015. Transfer Functions. <i>In</i> Handbook for Sea-Level Research.
977	<i>Edited by</i> I. Shennan and A.J. Long and B.P. Horton. John Wiley & Sons, Chichester. pp.
978	470-499.
979	Kemp, A.C., Wright, A.J., and Cahill, N. 2020. Enough is enough, or more is more? Testing the
980	influence of foraminiferal count size on reconstructions of paleo-marsh elevation. Journal
981	of Foraminiferal Research, 50: 266-278. doi:https://doi.org/10.2113/gsjfr.50.3.266.
982 983 984	 Kemp, A.C., Shaw, T.A., and Piecuch, C.G. 2022. The importance of non-tidal water-level variability for reconstructing Holocene relative sea level. Quaternary Science Reviews, 290: 107637. doi:https://doi.org/10.1016/j.quascirev.2022.107637.
985	Kemp, A.C., Whetstine, E., and Ridge, J.C. 2024. Chronology of late Holocene relative sea-level
986	change in Boston Harbor. Quaternary Science Reviews, 346: 109053.
987	doi:https://doi.org/10.1016/j.quascirev.2024.109053.
988	Kemp, A.C., Vane, C.H., Horton, B.P., Engelhart, S.E., and Nikitina, D. 2012. Application of
989	stable carbon isotopes for reconstructing salt-marsh floral zones and relative sea level,
990	New Jersey, USA. Journal of Quaternary Science, 27: 404-414.
991	doi:https://doi.org/10.1002/jqs.1561.
992	Kemp, A.C., Cahill, N., Engelhart, S.E., Hawkes, A.D., and Wang, K. 2018. Revising estimates
993	of spatially variable subsidence during the A.D. 1700 Cascadia earthquake using a
994	Bayesian foraminiferal transfer function. Bulletin of the Seismological Society of
995	America, 108: 654-673. doi:https://doi.org/10.1785/0120170269.
996	Kemp, A.C., Wright, A.J., Barnett, R.L., Hawkes, A.D., Charman, D.J., Sameshima, C., King,
997	A.N., Mooney, H.C., Edwards, R.L., and Horton, B.P. 2017. Utility of salt-marsh
998	foraminifera, testate amoebae and bulk-sediment δ ¹³ C values as sea-level indicators in
999	Newfoundland, Canada. Marine Micropaleontology, 130 : 43-59.
1000	doi:https://doi.org/10.1016/j.marmicro.2016.12.003.

1001	Kwak, T.J., and Zedler, J.B. 1997. Food web analysis of southern California coastal wetlands
1002	using multiple stable isotopes. Oecologia, 110 : 262-277.
1003	doi:https://doi.org/10.1007/s004420050159.
1004	Kwon, E.Y., Timmermann, A., Tipple, B.J., and Schmittner, A. 2022. Projected reversal of
1005	oceanic stable carbon isotope ratio depth gradient with continued anthropogenic carbon
1006	emissions. Communications Earth & Environment, 3: 62.
1007	doi:https://doi.org/10.1038/s43247-022-00388-8.
1008	Lamb, A.L., Wilson, G.P., and Leng, M.J. 2006. A review of coastal palaeoclimate and relative
1009	sea-level reconstructions using δ ¹³ C and C/N ratios in organic material. Earth-Science
1010	Reviews, 75 : 29-57. doi:https://doi.org/10.1016/j.earscirev.2005.10.003.
1011	Lu, Y., Thompson, K.R., and Wright, D.G. 2001. Tidal currents and mixing in the Gulf of St.
1012	Lawrence: an application of the incremental approach to data assimilation. Canadian
1013	Journal of Fisheries and Aquatic Sciences, 58: 723-735. doi:https://doi.org/10.1139/f01-
1014	011.
1015	Malamud-Roam, F., and Ingram, B.L. 2004. Late Holocene δ ¹³ C and pollen records of
1016	paleosalinity from tidal marshes in the San Francisco Bay estuary, California. Quaternary
1017	Research, 62: 134-145. doi:https://doi.org/10.1016/j.yqres.2004.02.011.
1018	Middleburg, J.J., Nieuwenhuize, J., Lubberts, R.K., and van de Plassche, O. 1997. Organic
1019	carbon isotope systematics of coastal marshes. Estuarine Coastal and Shelf Science, 45:
1020	681-687. doi:https://doi.org/10.1006/ecss.1997.0247.
1021 1022 1023 1024	Patterson, R.T., Roland Gehrels, W., Belknap, D.F., and Dalby, A.P. 2004. The distribution of salt marsh foraminifera at Little Dipper Harbour New Brunswick, Canada: implications for development of widely applicable transfer functions in sea-level research. Quaternary International, 120 : 185-194. doi:http://dx.doi.org/10.1016/j.quaint.2004.01.017.
1025	Peteet, D.M., Nichols, J., Kenna, T., Chang, C., Browne, J., Reza, M., Kovari, S., Liberman, L.,
1026	and Stern-Protz, S. 2018. Sediment starvation destroys New York City marshes'
1027	resistance to sea level rise. Proceedings of the National Academy of Sciences.
1028	doi:https://doi.org/10.1073/pnas.1715392115.
1029 1030 1031	Peterson, B.J., and Howarth, R.W. 1987. Sulfur, carbon, and nitrogen isotopes used to trace organic matter flow in the salt-marsh estuaries of Sapelo Island, Georgia. Limnology and Oceanography, 32 : 1195-1213. doi:https://doi.org/10.4319/lo.1987.32.6.1195.
1032 1033 1034	Peterson, B.J., Howarth, R.W., and Garritt, R.H. 1985. Multiple stable isotopes used to trace the flow of organic matter in estuarine food webs. Science, 227 : 1361-1363. doi:https://doi.org/10.1126/science.227.4692.1361.
1035	Plater, A.J., Kirby, J.R., Boyle, J.F., Shaw, T., and Mills, H. 2015. Loss on ignition and organic
1036	content. <i>In</i> Handbook of Sea-Level Research. <i>Edited by</i> I. Shennan and A.J. Long and
1037	B.P. Horton. John Wiley & Sons, Chichester. pp. 312-330.

1038	Pugh, D., and Woodworth, P.L. 2014. Sea-Level Science: Understanding Tides, Surges,
1039	Tsunamis and Mean Sea-Level Changes. Cambridge University Press.
1040	Raivo, K. 2018. pheatmap: Pretty Heatmaps.
1041	Rush, G., McDarby, P., Edwards, R., Milker, Y., Garrett, E., and Gehrels, W.R. 2021.
1042	Development of an intertidal foraminifera training set for the North Sea and an
1043	assessment of its application for Holocene sea-level reconstructions. Marine
1044	Micropaleontology, 169: 102055. doi:https://doi.org/10.1016/j.marmicro.2021.102055.
1045	Sage, R.F., Wedin, D.A., and Li, M. 1999. The Biogeography of C ₄ Photosynthesis: Patterns and
1046	Controlling Factors. In C ₄ Plant Biology. Edited by R.F. Sage and R.K. Monson.
1047	Academic Press, San Diego. pp. 313-374.
1048	Scott, D.B., and Medioli, F.S. 1978. Vertical zonations of marsh foraminifera as accurate
1049	indicators of former sea levels. Nature, 272: 528-531.
1050	doi:https://doi.org/10.1038/272528a0.
1051	Scott, D.B., and Medioli, F.S. 1980. Quantitative studies of marsh foraminiferal distributions in
1052	Nova Scotia: implications for sea level studies. Cushman Foundation for Foraminiferal
1053	Research, 17.
1054	Scott, D.B., Williamson, M.A., and Duffett, T.E. 1981. Marsh foraminifera of Prince Edward
1055	Island: their recent distribution and application for former sea-level studies. Maritime
1056	Sediments and Atlantic Geology, 17: 98-129.
1057 1058	Shennan, I. 2015. Framing Research Questions. <i>In</i> Handbook of sea-level research. <i>Edited by</i> I. Shennan and A.J. Long and B.P. Horton. Wiley. pp. 3-25.
1059	Stearns, R.B., Engelhart, S.E., Kemp, A.C., Hill, T.D., Brain, M.J., and Corbett, D.R. 2023.
1060	Within-region replication of late Holocene relative sea-level change: An example from
1061	southern New England, United States. Quaternary Science Reviews, 300 : 107868.
1062	doi:https://doi.org/10.1016/j.quascirev.2022.107868.
1063 1064 1065 1066 1067	Tanner, B.R., Uhle, M.E., Mora, C.I., Kelley, J.T., Schuneman, P.J., Lane, C.S., and Allen, E.S. 2010. Comparison of bulk and compound-specific δ ¹³ C analyses and determination of carbon sources to salt marsh sediments using n-alkane distributions (Maine, USA). Estuarine, Coastal and Shelf Science, 86 : 283-291. doi:https://doi.org/10.1016/j.ecss.2009.11.023.
1068	Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K., and Purcell, A.P. 2006. Tidal evolution
1069	of the northwest European shelf seas from the Last Glacial Maximum to the present.
1070	Journal of Geophysical Research: Oceans, 111.
1071	doi:https://doi.org/10.1029/2006JC003531.
1072	Vacchi, M., Engelhart, S.E., Nikitina, D., Ashe, E.L., Peltier, W.R., Roy, K., Kopp, R.E., and
1073	Horton, B.P. 2018. Postglacial relative sea-level histories along the eastern Canadian

1074	coastline. Quaternary Science Reviews, 201 : 124-146.
1075	doi:https://doi.org/10.1016/j.quascirev.2018.09.043.
1076	Velay-Vitow, J., Peltier, W.R., and Stuhne, G.R. 2020. The tides of the glacial ocean and their
1077	possible connection to Heinrich Event instabilities of the Laurentide Ice Sheet. Journal of
1078	Geophysical Research: Oceans, 125 : e2019JC015444.
1079	doi:https://doi.org/10.1029/2019JC015444.
1080 1081	Velinsky, D.J., Paudel, B., Belton, T.J., and Sommerfield, C.K. 2017. Tidal marsh record of nutrient loadings in Barnegat Bay, New Jersey. Journal of Coastal Research: 79-88.
1082	Walker, J.S., and Cahill, N. 2024. Influence of foraminifera count size and rare species on
1083	transfer function results used in sea-level reconstructions. Journal of Foraminiferal
1084	Research, 54: 107-116. doi:https://doi.org/10.61551/gsjfr.54.2.107.
1085	Walker, J.S., Cahill, N., Khan, N.S., Shaw, T.A., Barber, D., Miller, K.G., Kopp, R.E., and
1086	Horton, B.P. 2020. Incorporating temporal and spatial variability of salt-marsh
1087	foraminifera into sea-level reconstructions. Marine Geology, 429 : 106293.
1088	doi:https://doi.org/10.1016/j.margeo.2020.106293.
1089	Walker, J.S., Li, T., Shaw, T.A., Cahill, N., Barber, D.C., Brain, M.J., Kopp, R.E., Switzer, A.D.,
1090	and Horton, B.P. 2023. A 5000-year record of relative sea-level change in New Jersey,
1091	USA. The Holocene, 33 : 167-180. doi:https://doi.org/10.1177/09596836221131696.
1092	Walker, J.S., Kopp, R.E., Shaw, T.A., Cahill, N., Khan, N.S., Barber, D.C., Ashe, E.L., Brain,
1093	M.J., Clear, J.L., Corbett, D.R., and Horton, B.P. 2021. Common Era sea-level budgets
1094	along the U.S. Atlantic coast. Nature Communications, 12: 1841.
1095	doi:https://doi.org/10.1038/s41467-021-22079-2.
1096 1097	Walton, W.R. 1952. Techniques for recognition of living foraminifera. Cushman Foundation for Foraminiferal Research, 3 : 56-60.
1098	Williams, S., Garrett, E., Moss, P., Bartlett, R., and Gehrels, W.R. 2021. Development of a
1099	training set of contemporary salt-marsh foraminifera for late Holocene sea-level
1100	reconstructions in southeastern Australia. Open Quaternary, 7: 4. doi:
1101	http://doi.org/10.5334/oq.93.
1102	Wilson, G.P. 2017. On the application of contemporary bulk sediment organic carbon isotope
1103	and geochemical datasets for Holocene sea-level reconstruction in NW Europe.
1104	Geochimica et Cosmochimica Acta, 214: 191-208.
1105	doi:https://doi.org/10.1016/j.gca.2017.07.038.
1106 1107 1108 1109	Wilson, G.P., Lloyd, J., Khan, N.S., and Kemp, A.C. 2024. Developments in the application of stable carbon isotopes and bulk geochemistry as indicators of relative sea-level change in tidal wetlands and isolation basins. Quaternary Science Reviews, 340 : 108855. doi:https://doi.org/10.1016/j.quascirev.2024.108855.

1110 1111 1112	Woodroffe, S., and Barlow, N.L.M. 2015. Reference Water Level and Tidal Datum. <i>In</i>Handbook of Sea-Level Research. <i>Edited by</i> I. Shennan and A.J. Long and B.P. Horton.John Wiley & Sons, Chichester. pp. 171-182.
1113	Wright, A.J., Edwards, R.J., and van de Plassche, O. 2011. Reassessing transfer-function
1114	performance in sea-level reconstruction based on benthic salt-marsh foraminifera from
1115	the Atlantic coast of NE North America. Marine Micropaleontology, 81: 43-62.
1116	doi:https://doi.org/10.1016/j.marmicro.2011.07.003.
1117	Zhang, D., Wang, H., Liu, X., Ao, K., He, W., Wang, T., Zhang, M., and Tong, S. 2024.
1118	Latitudinal patterns and their climate drivers of the δ ¹³ C, δ ¹⁵ N, δ ³⁴ S isotope signatures of
1119	<i>Spartina alterniflora</i> across plant life-death status: a global analysis. Frontiers in Plant
1120	Science, 15 : 1384914. doi:https://doi.org/10.3389/fpls.2024.1384914.
1121	Zong, Y., and Horton, B.P. 1999. Diatom-based tidal-level transfer functions as an aid in
1122	reconstructing Quaternary history of sea-level movements in the UK. Journal of
1123	Quaternary Science, 14: 153-167. doi:https://doi.org/10.1002/(SICI)1099-
1124	1417(199903)14:2%3C153::AID-JQS425%3E3.0.CO;2-6.

















