



Reconstruction of recent sea-level change using testate amoebae

Dan J. Charman^{a,*}, W. Roland Gehrels^b, Clare Manning^b, Charu Sharma^c

^a School of Geography, University of Exeter, Exeter, EX4 4RJ, UK

^b School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, Devon, PL4 8AA, UK

^c School of Marine Science and Engineering, University of Plymouth, Plymouth, Devon, PL4 8AA, UK

ARTICLE INFO

Article history:

Received 6 March 2009

Available online 2 February 2010

Keywords:

Sea-level reconstruction

Testate amoebae

Saltmarsh

Foraminifera

Tide-gauge

ABSTRACT

Proxy-based sea-level reconstructions place the instrumentally observed rates of recent sea-level rise in a longer term context by providing data that extend the instrumental sea-level record into past centuries. This paper presents the first sea-level reconstructions based on analyses of testate amoebae, to test their ability to produce high-precision reconstructions of past sea level. We present two reconstructions for the past 100 yr from sites in Maine (USA) and Nova Scotia (Canada) based on short cores from salt marshes, and modern training data from North America and the United Kingdom. These are compared with tide-gauge records and reconstructions based on foraminifera from the same cores. The reconstructions show good agreement with both the tide-gauge data and the foraminifera-based reconstructions. The UK data perform well in predicting known elevations of North American surface samples and produce sea-level reconstructions very similar to those based on the North American data, suggesting the methodology is robust across large geographical areas. We conclude that testate amoebae have the potential to provide robust, higher precision sea-level reconstructions for the past few centuries if modern transfer functions are improved and core sites are located within the main zone of testate amoebae occurrence on the salt marsh.

© 2009 University of Washington. Published by Elsevier Inc. All rights reserved.

Introduction

Sea-level change is one of the most important aspects of future global change and understanding the causes, rates and geographical and temporal variability of sea level is crucial to improving predictions of 21st century sea-level rise. Measurements and reconstructions of past sea level play an important part in improving understanding of sea-level change (Bindoff et al., 2007). Tide-gauge records and satellite data provide high temporal resolution data, but the temporal and spatial coverage of these records is limited. Reconstructions of sea-level change over the past few millennia are therefore critical to understanding the dynamics of sea-level change and there are a growing number of reconstructions for locations around the world (e.g., Varekamp et al., 1992; van de Plassche et al., 1998; Gehrels et al., 2002, 2005, 2008; Donnelly et al., 2004). Recent research has used high temporal resolution records to show that current rates of sea-level rise are two to three times faster than longer term rates over previous centuries (Gehrels et al., 2005). While this longer term context for individual locations is important, it does not necessarily help test hypotheses concerning the causes and sources of the recent acceleration in sea-level rise, unless an appropriate spatial and temporal network of reconstructions exists. Adequate spatial and temporal coverage of sea-level change over the last few hundred years

can only be provided by palaeoenvironmental records due to the spatial bias in tide-gauge records to the northern hemisphere.

The most detailed and precise late Holocene sea-level reconstructions are based on the use of salt-marsh foraminifera as sea-level indicators. Statistical analyses indicate that in most locations the precision of sea-level positions reconstructed from foraminifera is on the order of ± 20 cm (Horton et al., 1999a,b; Edwards and Horton, 2000; Gehrels, 2000) while only along microtidal coastlines, such as the Atlantic coast of Nova Scotia, Canada, the precision is better than ± 10 cm (Gehrels et al., 2005). In most mid-latitude North Atlantic locations, the rise of sea level in the past century has been around 10–20 cm (Holgate, 2007; Woodworth et al., 2008). If an attempt is made to detect the onset of this recent rapid rise, it is therefore desirable to use sea-level indicators that have higher precision than those offered by foraminifera. Diatoms improve precision in some contexts but testate amoebae appear to have particular potential as high-precision indicators in salt-marsh sediments with tightly constrained zonation in relation to elevation in the upper marsh and supra-tidal zones (Charman et al., 1998, 2002; Gehrels et al., 2001). However, apart from an initial assessment of samples from a range of sedimentary contexts (Roe et al., 2002), there have been no attempts to use testate amoebae to develop and test high-resolution records of sea-level change.

This paper reports the results of testate amoebae analysis on two salt-marsh cores from the Atlantic coast of North America to demonstrate the use of testate amoebae as high-precision sea-level indicators capable of detecting fluctuations of the order of ± 10 cm

* Corresponding author. Fax: +44 1392 263342.

E-mail address: d.j.charman@exeter.ac.uk (D.J. Charman).

over multi-decadal to centennial timescales. Our reconstructions are assessed against nearby tide-gauge data and published sea-level reconstructions based on foraminifera. We also suggest an improved preparation procedure that overcomes some of the difficulties associated with counting low concentrations of testate amoebae in organic silty sediments that are typical of high marsh settings (Roe et al., 2002).

Testate amoebae as sea-level indicators

Testate amoebae (or 'thecamoebians') are a group of test-forming protozoa some of which are related to foraminifera. They are known to be good indicators of hydrological conditions in peatlands (e.g., Tolonen, 1986; Charman et al., 2006). Testate amoebae have also been reported in salt-marsh environments (e.g., Scott et al., 1991, 1995a) in samples prepared for foraminiferal analyses, but only in low numbers and low diversity in the size fraction 63–500 μm . We have collected testate amoebae from surface sediments in salt marshes in the UK (Charman et al., 1998, 2000a, 2002; Gehrels et al., 2001; Roe et al., 2002) and along the eastern seaboard of North America (Gehrels et al., 2006). In these investigations, we have applied techniques commonly used in peatland studies (Hendon and Charman, 1997) and examined the fraction between 15 and 63 μm in addition to the 63- to 500- μm fraction. Our results indicate that small testate amoebae (<63 μm) are much more abundant and diverse in salt-marsh sediments than the larger testate amoebae (>63 μm). The vertical distribution of testate amoebae is distinctly zoned on the surface of salt marshes and shows a stronger zonation than that of diatoms and foraminifera in the highest levels of marshes (Gehrels et al., 2001). Testate amoebae can be found as low as the level of mean high spring tide, but their vertical extent reaches upward into areas well above the highest limit of foraminifera.

Based on quantitative analyses of modern datasets, we have concluded that testate amoebae may be capable of resolving sea-level positions with a precision perhaps as low as ± 4 cm in microtidal sites, provided that fossil testate amoebae are present and well preserved in subsurface sediments (Gehrels et al., 2006). This study represents the first systematic attempt to use fossil testate amoebae to reconstruct recent sea-level change and test reconstruction precision against temporal change rather than spatial cross-validation.

Site descriptions and previous work

We sampled cores from two previously studied sites in Maine and Nova Scotia (Fig. 1). The Webhannet marsh in Wells, Maine (43°18'N, 70°34'W), is a back-barrier marsh along the Wells embayment in southwestern Maine (USA). The marsh is connected to the Gulf of Maine by a flood-dominated tidal inlet and the mean tidal range in the marsh is 2.64 m (Gehrels, 1994). The sea-level history has previously been determined from salt-marsh plant fossils (Belknap et al., 1989) and foraminifera (Kelley et al., 1995; Gehrels et al., 1996, 2002). The core selected for the present study is core FS-1 from the high marsh zone where *Spartina patens* is the dominant plant cover. This core was first analysed for foraminifera by Gehrels et al. (2002) and formed the basis for a detailed sea-level chronology spanning the past 1200 yr. The sea-level curve for Wells compared well with a curve produced for Machiasport in eastern Maine and is therefore interpreted to be representative for the Gulf of Maine. In the past 100–200 yr, the Gulf of Maine has experienced 0.3–0.4 m of relative sea-level rise, the fastest rise in the past millennium. Gehrels et al. (2002) suggested that sea-level rise may have been slow in the middle of the 19th century, but the precision of their reconstruction precluded a clear distinction between pre- and post-industrial rates of sea-level rise.

The Chezzetcook Inlet is located 45 km ENE of Halifax, Nova Scotia (Canada), and is micro- to mesotidal with a tidal range of 2.14 m at the mouth of the inlet. Tidal range is reduced to 1.86 m at the West Head

location where core CZ-25 is located in the high marsh zone dominated by *S. patens* (Gehrels et al., 2005). Chezzetcook Inlet has been the site of previous Holocene sea-level studies, including those by Scott (1977), Scott et al. (1987, 1995b) and Gehrels et al. (2004, 2005). Gehrels et al. (2005) established a high-resolution sea-level reconstruction for the last 1000 yr based on foraminifera and showed a doubling of the rate of sea-level rise, from 1.6 to 3.2 mm yr⁻¹, shortly after ca. AD 1900.

Laboratory methods

Standard preparations for testate amoebae samples are water-based sieving to separate the 15- to 300- μm fraction for counting at 100–1000 \times magnification under a light microscope (Charman et al., 2000b). However, in fossil and some surface samples, this process retains a large amount of silt-sized organic remains that can obscure the tests, rendering samples difficult or impossible to count to totals that are appropriate for statistical analysis. Previous assessments on terrestrial peat have shown that typical pollen preparation processes and other chemical treatments damage or destroy tests and so are not generally used. However, low-strength alkali treatment prior to sieving can remove organic aggregates. Although there is some alteration of structure, tests are not destroyed and can still be identified (Hendon and Charman, 1997). We used a modified procedure of Hendon and Charman (1997), including pre-treatment with 5% KOH to eliminate unwanted detritus. We compared counts from eight test samples from the Wells core, with and without KOH treatment to assess the effects on test numbers and concentrations. Following this preliminary test, we applied the same preparation process to all fossil samples.

Samples of 0.2–0.5 ml from 1-cm-thick slices were collected from the cores and weighed. One tablet of *Lycopodium clavatum* L. was added as an exotic marker (Stockmarr, 1971). Samples were boiled in 100 ml distilled water for 5–10 min, stirred occasionally to aid disaggregation and left soaking overnight. The next day, samples were sieved and the fraction of 15–300 μm was retained for analysis. A 4-ml solution of 5% KOH was added and samples were warmed at approximately 80°C for 1–2 min and sieved again at 15 μm to remove more fine detritus. Finally, samples were mounted in glycerol or water onto a microscope slide with a 22 \times 40-mm coverslip sealed with nail varnish. In the initial test of KOH treatment, testate amoebae were counted until 150 *Lycopodium* spores had been counted. In the full counts of fossil samples, at least 50 tests were counted. The time-consuming nature of the counting procedure precluded the counting of more specimens, but the number of 50 individuals is sufficient in the absence of rare taxa (those that occur in very low abundances of perhaps <5%; Patterson and Fishbein, 1989). Data from some samples with <50 specimens are also included in the Results section but these data are not used for transfer functions or sea-level reconstructions.

A series of transfer functions based on surface samples of testate amoebae were applied to the fossil data using the program C2 (Juggins, 2003). Two main data sets were used for this. First, we tested several different transfer functions based on data from two marshes in the region, consisting of 29 surface samples from the Little River Marsh (approximately 4 km from the Wells core site) and the Little Dipper Harbour marsh in New Brunswick (Gehrels et al., 2006). These data sets are illustrated in Figure 2 as taxon abundance plotted against surface elevation and show the strong zonation of taxa along the tidal gradient. We also applied a local transfer function to the Wells data based only on the 17 samples from the Little River Marsh, although this has the disadvantage that sample numbers are too low to generate sample-specific error estimates. Second, we tested a similar series of transfer functions based on modern data from the United Kingdom (Charman et al., 2002) to test whether taxon–environment relationships are robust across the North Atlantic region. If modern relationships are spatially

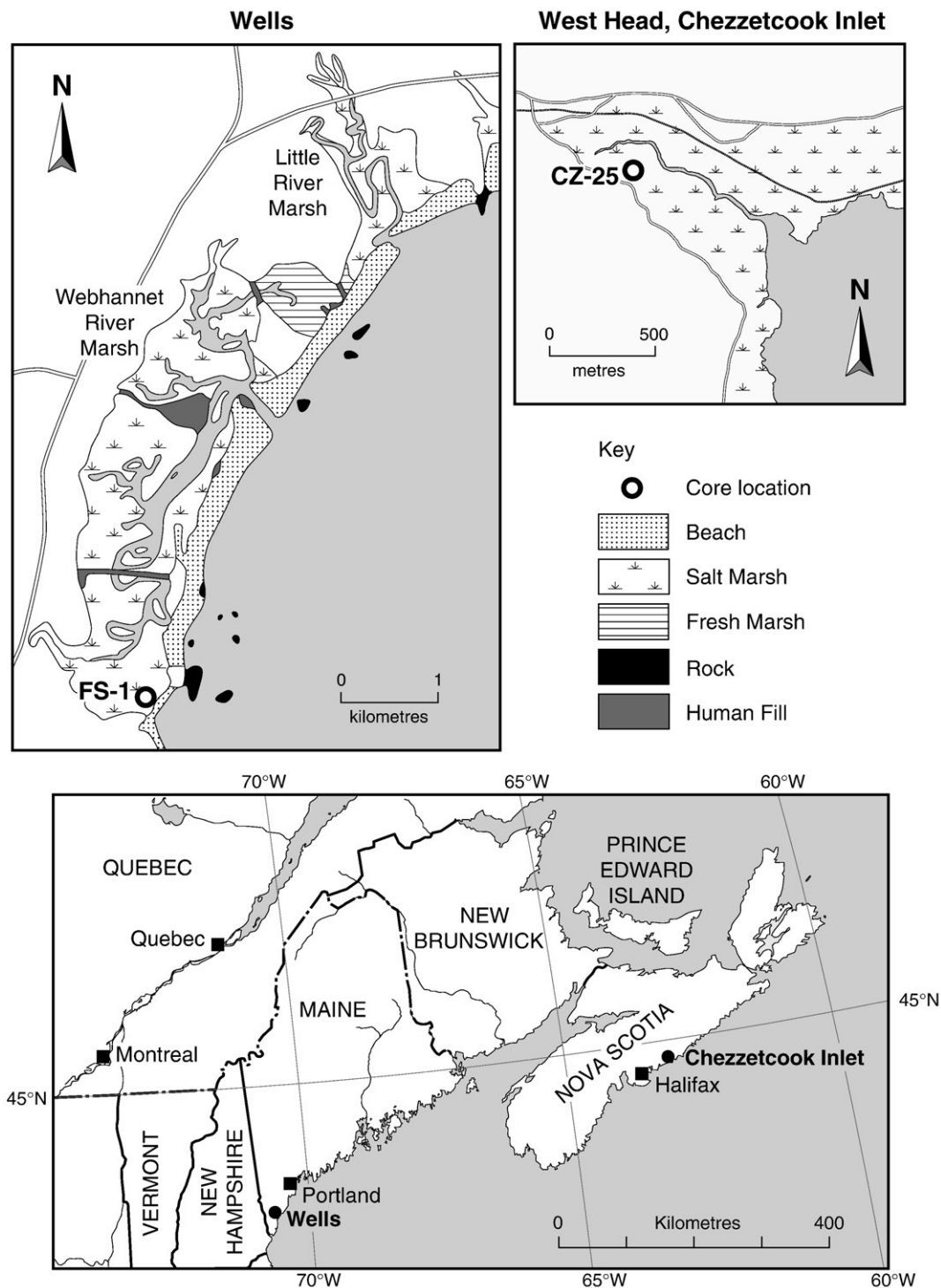


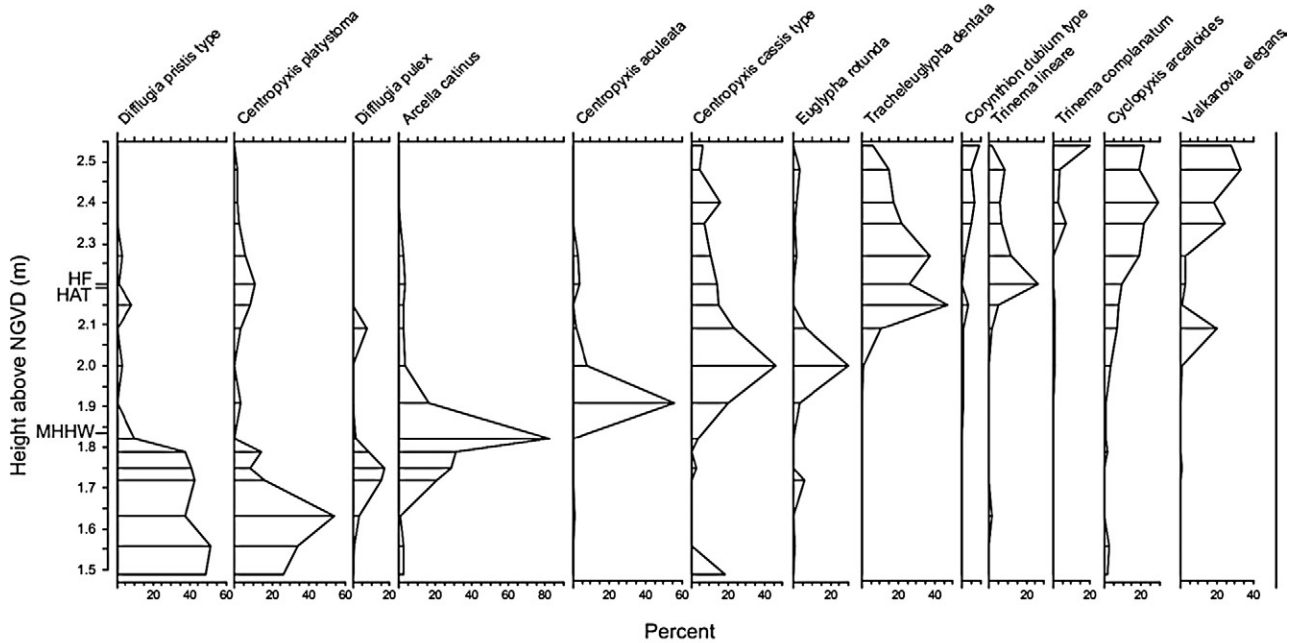
Figure 1. Locations for the core sites. See Gehrels et al. (2006) and Charman et al. (2002) for details of modern sampling sites.

robust, it is more likely that the transfer functions are also temporally robust. To assess this, the best performing transfer function in cross-validation of the UK data was applied to the modern North American samples as well as to the fossil samples. In order to combine data from sites with different tidal ranges, elevation data were normalised in relation to the difference between mean tidal level (MTL) and highest astronomical tide (HAT).

The chronologies for the cores were based on radiocarbon, ^{210}Pb , ^{137}Cs , $^{207}\text{Pb}/^{206}\text{Pb}$ ratios and pollen analyses (Gehrels et al., 2002, 2005). For Chezzetcook, the age–depth model is based on ^{210}Pb ages for the upper part of the profile, cross-checked against

^{207}Pb : ^{206}Pb ratios and ^{137}Cs , and extrapolated for ages prior to ca. AD 1890 to a pollen marker at AD 1780 ± 20 yr (Gehrels et al., 2005, Fig. 8b). For Wells, the chronology is based on ^{210}Pb cross-checked against ^{137}Cs and extrapolated to a pollen marker at AD 1760 (Gehrels et al., 2002, Fig. 2). The samples used for testate amoebae analysis date almost entirely from the sections of the cores dated by ^{210}Pb to post-AD 1900, supported by ^{137}Cs and ^{207}Pb : ^{206}Pb ratios. For the Wells core, we also tested for the presence of spheroidal carbonaceous particles (SCPs), markers for industrial pollution found widely in lake and peat sediments but not reported from salt-marsh deposits (Rose, 2002).

a) Little River marsh, Wells, Maine
Testate amoebae



b) Little Dipper Harbour marsh, New Brunswick
Testate amoebae

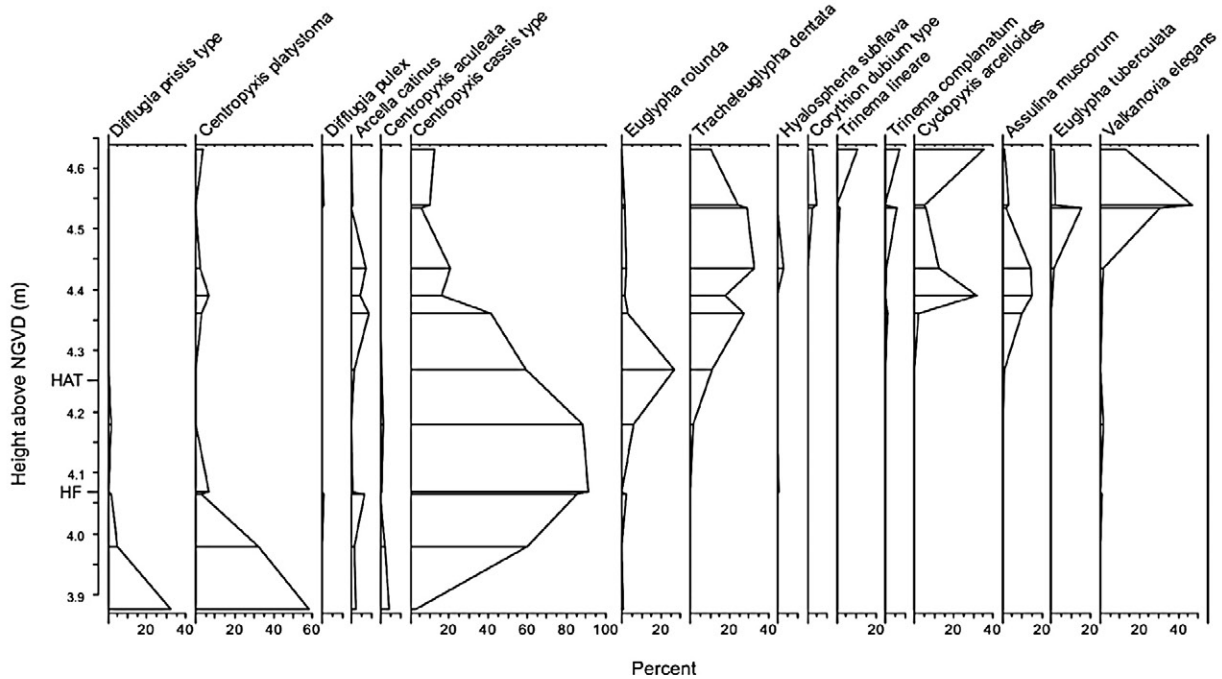


Figure 2. Modern testate amoebae data plotted against elevation from the marshes used in the North American transfer function. (a) Little River marsh, Wells, Maine; (b) Little Dipper Harbour Marsh, New Brunswick. The tidal data shown on the height axis are highest astronomical tide (HAT) and mean highest high water (MHHW). HF is the maximum height of foraminifera recorded in the 63- to 500- μm size range.

Results

Effect of KOH treatment

A total of 60 tests were counted in the eight samples prepared by standard water-based techniques (Table 1). Both the count (29) and the concentration (56.4 mg^{-1}) were highest in the sample from 8 to 9 cm depth, with other samples having counts between 1 and 8 tests,

representing concentrations of 4.9–18.1 tests mg^{-1} . Counts were higher overall in the samples treated with KOH (71 tests counted) and concentrations were also increased in the samples from 32 cm and above where counts were highest. Deeper samples had very low counts (<10) and concentrations (<10 mg^{-1}) in both treatments and generally showed reduced counts and concentrations following KOH treatment. The assemblage composition of the samples with counts > 10 is very similar between treatments with most of the same

Table 1
Testate amoebae counts from standard (upper) and KOH-based (lower) sample pre-treatment for eight samples from the Wells core. Total no. tests counted in left hand column. All other figures are concentrations (nos. mg⁻¹ wet weight sample).

Depth (cm)	Count	<i>Trinema lineare</i>	<i>Corythion dubium</i>	<i>Diffflugia pristis</i>	<i>Diffflugia pulex</i>	<i>Diffflugia</i> type	<i>Pseudodiffflugia fulva</i>	<i>Centropyxis cassis</i>	<i>Cyphoderia</i>	<i>Arcella catinus</i>	<i>Euglypha rotunda</i>	Unknown	Total
8–9	29	1.9		7.8	3.9	11.7			1.9	27.2		1.9	56.4
16–17	6							1.2		4.6		1.2	7.0
24–25	4			2.8			5.6	2.8					11.2
31–32	3		6.0					6.0				6.0	18.1
40–41	1											4.9	4.9
48–49	3									4.9			4.9
57–58	6					2.6	2.6			2.6			7.9
65–66	8					1.9				5.7			7.6
Total	60	1.9	6.0	10.6	3.9	16.2	8.2	10.0	1.9	45.1	0.0	14.0	117.9
5% KOH													
8–9	41			23.3		5.8			5.8	44.7			79.7
16–17	13			4.6					3.5	7.0			15.1
24–25	12			8.4				8.4			8.4	5.6	33.5
31–32	4	6.0						12.1				6.0	24.2
40–41	0												
48–49	0												
57–58	1						1.3						1.3
65–66	0												
Total	71	6.0	0.0	36.3	5.8	14.9	1.3	8.4	9.3	51.7	8.4	11.6	153.7

dominant taxa present. Furthermore, although we did not quantify counting effort, the slides were generally clearer with better dispersal of material and reduced amounts of fine organic material visible. We conclude that the weak 5% KOH treatment improves overall quality of slides without selective effects on the assemblage. Increased concentrations in the KOH treatment suggest that tests are hidden by detritus in the water-based treatment. Although the numbers and range of samples and tests counted was not adequate to be conclusive, the results also indicate that damage to tests was not significant enough to prevent detection and identification of all taxa.

Hendon and Charman (1997) also reported increased concentrations of tests following a stronger 10% KOH treatment but found significant damage to tests. Our results suggest a lower concentration of KOH retains the benefit of reduced detritus while avoiding problems of test damage. This is an area still requiring further work and a systematic experiment to determine optimum combinations of KOH concentration, temperature and length of treatment. It seems likely that weak alkali treatments of problematic samples with low test concentrations improves counting efficiency and increases the numbers of samples from which data can be obtained, but we would not advocate using this process in the absence of some evaluation of its impact on specific samples and assemblages.

Modern assemblages and transfer functions

North American data

The modern assemblages (Fig. 2) show a strong zonation from elevations below mean higher high water (MHHW) extending to well above highest astronomical tide (HAT) and zonation is similar for both sites. A full discussion of the modern assemblages is given by Gehrels et al. (2006), but we include these data here to allow comparison with the fossil assemblages. The highest occurrence of foraminifera is at (Little River) or just below (Little Dipper) HAT, where dominant testate amoebae are *Centropyxis cassis* type, *Euglypha rotunda* type and *Tracheleuglypha dentata*. The lowermost samples are dominated by taxa such as *Diffflugia pristis* type and *Centropyxis platystoma* type.

Transfer functions based on weighted averaging performed best in leave-one-out cross-validation (Table 2), with no improvement from using a partial least squares (PLS) version of weighted averaging (WAPLS). A linear-based PLS model performed similarly and two approaches based on modern analogue matching (WAT and WMAT) were significantly worse. The weighted average model based on

classic deshrinking (WA_Cla) had the highest r^2 (0.85), lowest maximum bias and low RMSEP and was applied to the fossil data sets. For comparison with a tolerance downweighted model, which is potentially more stable in reconstructions, the WAT_Cla model was also applied.

UK data

The UK data set consists of modern samples from three sites (Taf estuary, south Wales; Erme estuary, Devon; Brancaster marsh, Norfolk). Previously, these data were used to examine a variety of relationships between testate amoebae and environmental conditions (Charman et al., 2002) and to test the potential of multi-proxy microfossil data for sea-level reconstructions (Gehrels et al., 2001). Here we test the ability of these data to estimate the known elevation of the modern samples from the North American marshes in order to assess the applicability of transfer functions over very wide geographical regions.

The transfer functions for the UK data suggest very good performance of some models (Table 3). In particular, the PLS model produced very high r^2 (0.99) and low RMSEP (0.012) values. The modern analogue technique also produced good cross-validation statistics ($r^2=0.61$, RMSEP=0.063), but the residuals were systematically biased with strong over-prediction in low-elevation samples and under-prediction in high-elevation samples (plot not shown). The best performing weighted average model (WAT_Inv; tolerance downweighted weighted average with inverse deshrinking) had a good r^2 (0.47) and low RMSEP (0.074). Both the PLS and WAT_Inv

Table 2

Transfer function performance in cross-validation using the leave-one-out (jack-knifing) method for the North American testate amoebae data. Results of WAPLS were the same as for simple weighted averaging and are not shown here. Root mean squared error of prediction (RMSEP) and bias data are for elevation normalised to the difference between mean tide level and highest astronomical tide.

Model	r^2	Average bias	Max. bias	RMSEP
WA_Inv	0.84	-0.0027	0.104	0.053
WA_Cla	0.85	-0.0034	0.084	0.054
WAT_Inv	0.80	-0.0047	0.123	0.059
WAT_Cla	0.81	-0.0055	0.099	0.060
PLS	0.81	-0.0011	0.095	0.057
MAT	0.78	-0.0173	0.166	0.068
WMAT	0.80	-0.0120	0.124	0.061

Table 3

Model performance results for the UK testate amoebae data (a) in cross-validation using normalised (MTL-HAT) data, and (b) applied to normalised modern US data. For b, the RMSEP is calculated on the errors between the observed and predicted values shown in Figure 3.

Model and application	r^2	RMSEP
<i>(a) Cross-validation</i>		
WA_Inv (weighted average, inverse deshrinking)	0.41	0.076
WA_Cla (weighted average, classical deshrinking)	0.43	0.098
WAT_Inv (tolerance downweighted weighted average, inverse deshrinking)	0.45	0.074
WAT_Cla (tolerance downweighted weighted average, classical deshrinking)	0.47	0.104
WAPLS Component 3 (weighted average partial least squares)	0.42	0.077
PLS Component 5 (partial least squares)	0.99	0.012
MAT (modern analogue)	0.44	0.074
WMAT (weighted modern analogue)	0.61	0.063
<i>(b) Applied to US data</i>		
WAT_Inv		0.083
PLS Component 5		0.101

models were applied to the US samples to assess their applicability to North American data (Table 3, Fig. 3). Performance in terms of RMSEP (Table 3) was surprisingly good for both transfer functions, although both tended to show a systematic bias towards over-prediction at low elevations and under-predictions at higher elevations (Fig. 3a). This tendency was much more extreme for the PLS model.

Normalising the data to the height between MTL and HAT is necessary in order to take account of differing tidal range between sites for transfer function development based on more than one site. For reconstruction of past sea level, however, these values are converted back to actual elevation using the modern tidal range for the site concerned. It is assumed that tidal range remained unchanged, which is reasonable for reconstructions covering only the last 100 yr. We therefore tested the ability of different transfer functions to estimate the actual elevation for the modern samples at the US sites, as an improved test of model performance (Fig. 3b, c). The tendency of the PLS model to underestimate the difference in elevation between samples was even more marked here, whereas the WAT_Inv model either slightly underestimated (Little River) or slightly overestimated (Little Dipper) this difference. Although the PLS model shows consistently higher statistical performance in cross-validation (Table 3) than the WAT_Inv model, the WAT_Inv model is therefore a much more robust model for reconstructions. In particular, the characteristics of the WAT_Inv model mean that it is much more likely to give accurate estimates of multi-decadal trends in reconstructions from fossil samples, a key aim in high temporal resolution studies (e.g., Gehrels et al., 2002, 2005, 2008).

Both models systematically underestimate elevation for the Little Dipper site and slightly overestimate elevation for the Little River marsh, suggesting the normalisation is not accurate, perhaps due to inaccuracy of the elevations for MTL and especially for HAT. The UK WAT_Inv model was applied to the Wells fossil data using a correction based on the average over-prediction for the Little River modern samples. No correction was applied to Chezzetcook fossil samples, as no modern data were available to estimate the prediction offset at this site.

Sea-level reconstructions

Wells

Tests were present in the top 19 cm of the Wells core, with only very low numbers below this level (Fig. 4, Table 1). Concentrations were up to 30,000 tests g^{-1} but were generally much lower at 5–13,000 tests g^{-1} (and only 1000–2500 tests g^{-1} in the samples 13–16 cm depth). Below 16 cm, concentrations fell to 100–500 tests g^{-1} ,

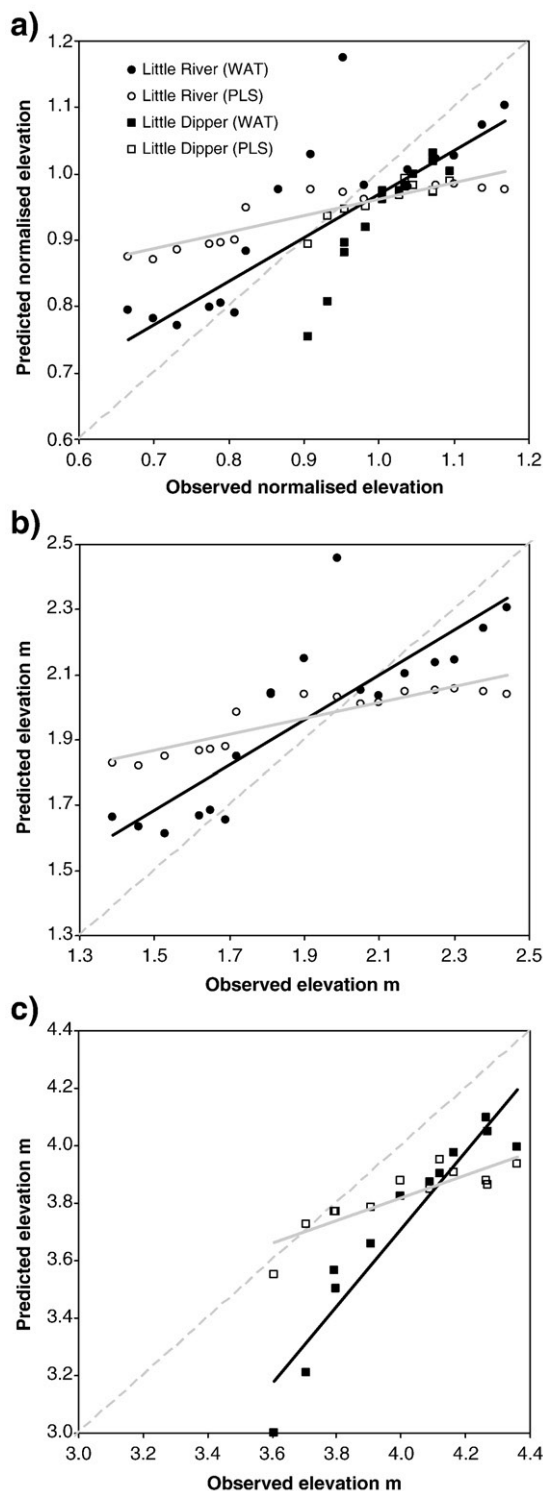


Figure 3. Comparison between observed sample elevations for the modern North American samples and their predicted elevations based on the UK transfer function applied to the testate amoebae assemblages. (a) For all samples plotted as elevation normalised for tidal range (MTL-HAT). (b and c) For untransformed elevations in height above MTL, (b) Little River and (c) Little Dipper Harbour. Circles—Little River; squares—Little Dipper; open—PLS model; closed—WAT model. Linear regression lines shown as black (WAT model) and grey (PLS model). Grey dashed line—1:1 line.

and no tests were found in a sample from 22 to 23 cm despite counting 200 *Lycopodium* spores.

For the purposes of comparison with tide-gauge data, we focused on the top part of the profile which is dated to the 20th century. Details of the chronological methods are given in Gehrels et al. (2002),

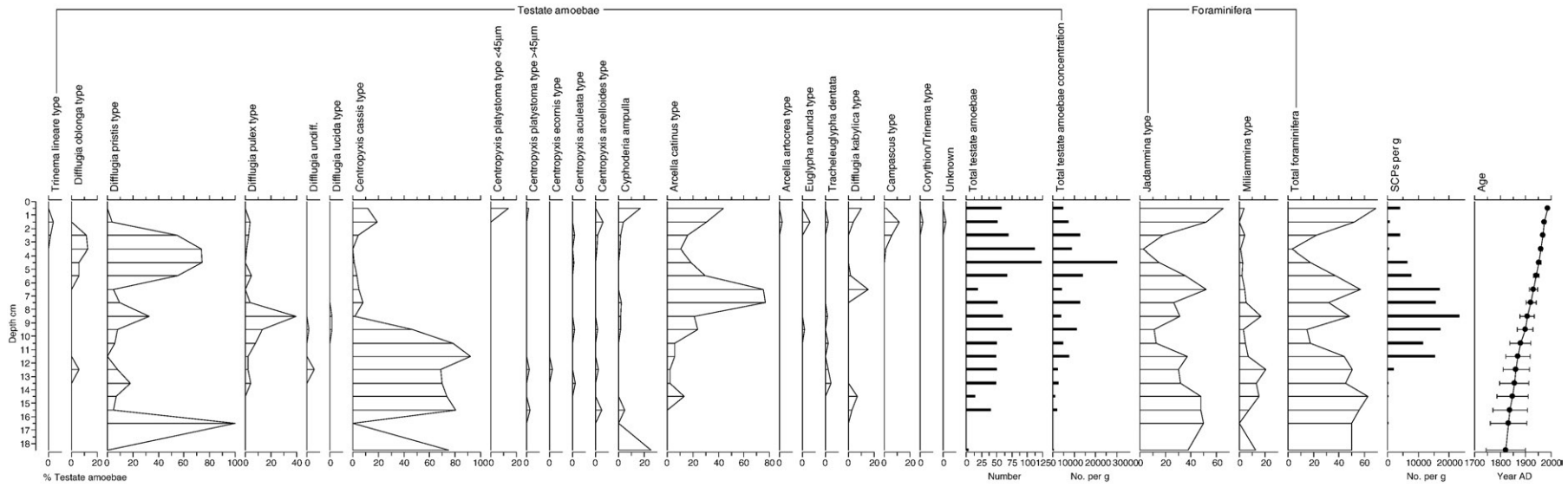


Figure 4. Testate amoebae diagram for core FS-1, Wells, showing all samples, including those with low total counts. A further sample at 22.5 cm contained no testate amoebae or foraminifera. The estimated ages are shown with 2σ errors based on ^{210}Pb analyses.

but for this site we also tested the use of SCPs for dating. The SCP curve shows the first major consistent presence of SCPs at about 12 cm depth, dated to ca. AD 1866 by extrapolating between the pollen marker and the lowermost reliable ^{210}Pb ages. A mid-19th century age is typical for the start of SCP curves in Europe, but this has not yet been established for North America. Given the lack of sites with independently estimated ages for SCP curves, it is not yet possible to use SCPs as an absolute age marker in this region. However, if adopted more widely for sediment dating, it would provide a valuable relative age marker and ultimately a useful additional chronological tool for eastern North America.

In the lower part of the profile (9–16 cm depth), the testate amoeba assemblage is dominated by *C. cassis* type and above 9 cm depth *Arcella catinus* type and *D. pristis* type are the most abundant taxa. Other more minor taxa occur throughout the profile, notably other *Centropyxis* and *Diffugia* types, *Cyphoderia ampulla*, *Corythion/Trinema* types and *T. dentata*. All these taxa have been previously reported from this or other North American marshes (Gehrels et al., 2006), with the exception of *Campascus* type, previously only reported from the United Kingdom (Charman et al., 2000a).

With the exception of one sample, total test counts exceeded 50 for the nine samples representing the 20th century, and reconstructions based on transfer functions were carried out on these samples

(Fig. 5). All the transfer functions suggest a generally rising trend in sea level through the 20th century. However, the uppermost samples suggest a decline in reconstructed sea level, related to the appearance of small numbers of testate amoebae typical of very high marsh or freshwater conditions (e.g., *Centropyxis arcelloides* type, *Trinema lineare* type) as well as a reduction in *D. pristis* type (Fig. 4). This is in opposition to the trends in the tide-gauge data, which suggest a slight rise or flattening in sea level during this time.

The local transfer function shows lower amplitude fluctuations during this period and the tolerance downweighted version of the transfer function also reduces the more extreme values. The bootstrapped error estimates for the testate amoebae are approximately two-thirds of those for the foraminifera, and the tide-gauge data fall within the estimated reconstruction errors for both testate amoebae and foraminifera-based reconstructions, with the exception of the sample from the mid-1970s. This sample has consistently lower values for sea level but there were no foraminifera data available from the original counts made by Gehrels et al. (2002), so that it remains uncertain whether the deviation away from tide-gauge data is a result of problems with the testate amoebae data or of some factor that affected the core location itself (such as localised freshwater ingress).

Excluding this sample, the estimated rates of sea-level rise vary between 1.62 ± 0.17 and 2.20 ± 0.25 mm yr^{-1} for the testate

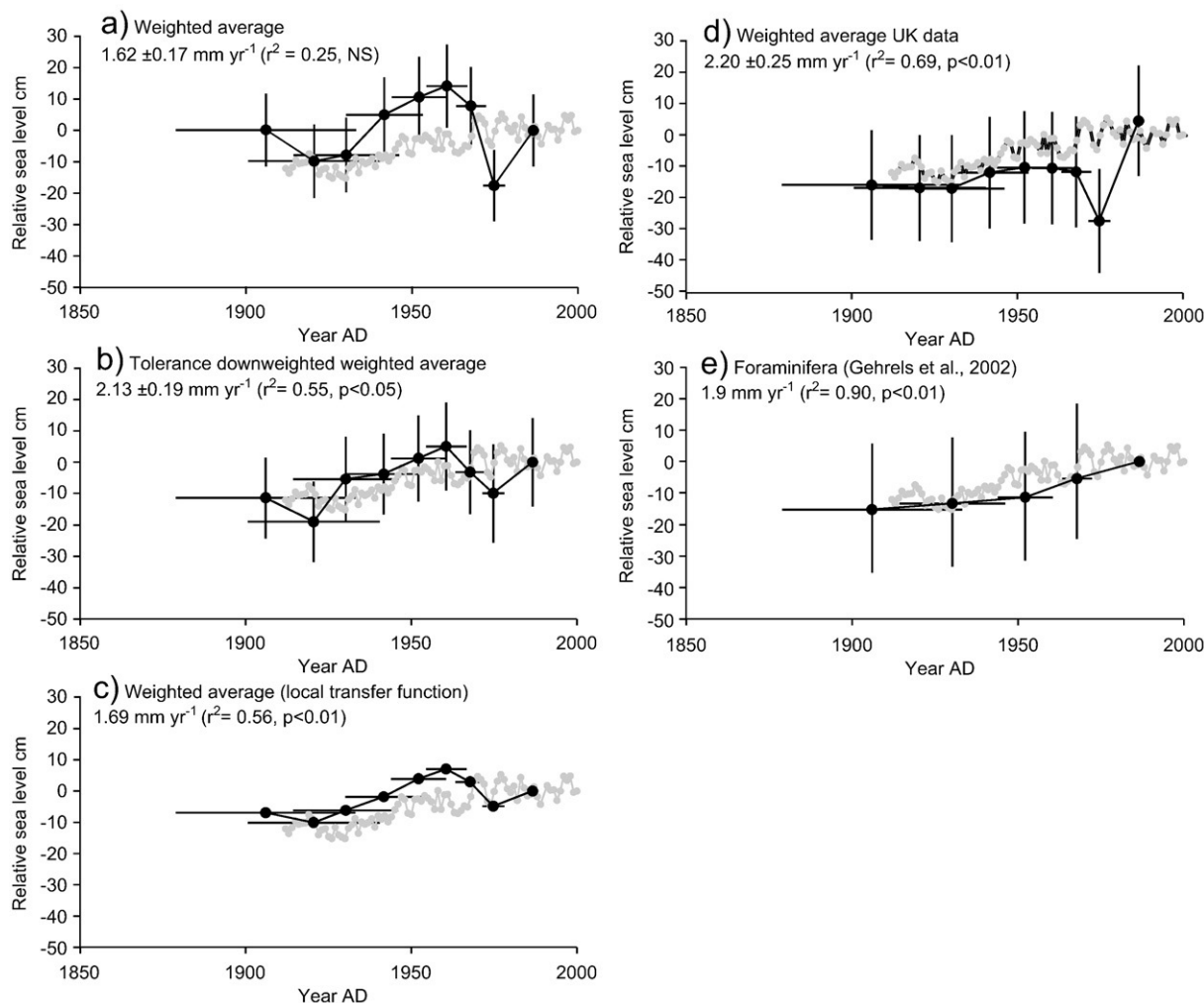


Figure 5. Comparison between reconstructions for the Wells core based on testate amoebae, foraminifera and the tide-gauge record from Portland, Maine (grey symbols). The rates of sea-level change are the linear trends over the period covered by the tide-gauge record. The rates for testate amoebae exclude the sample from the mid-1970s, which gives consistently lower values and is not represented in the foraminifera samples. For comparison, the linear trend of the tide-gauge record is 1.86 ± 0.12 mm yr^{-1} . Vertical error bars are RMSEP from transfer functions. Age error bars are 2σ errors from age–depth model. No RMSEP values calculated for panel c because of the low number of samples ($n = 17$) in the local training set.

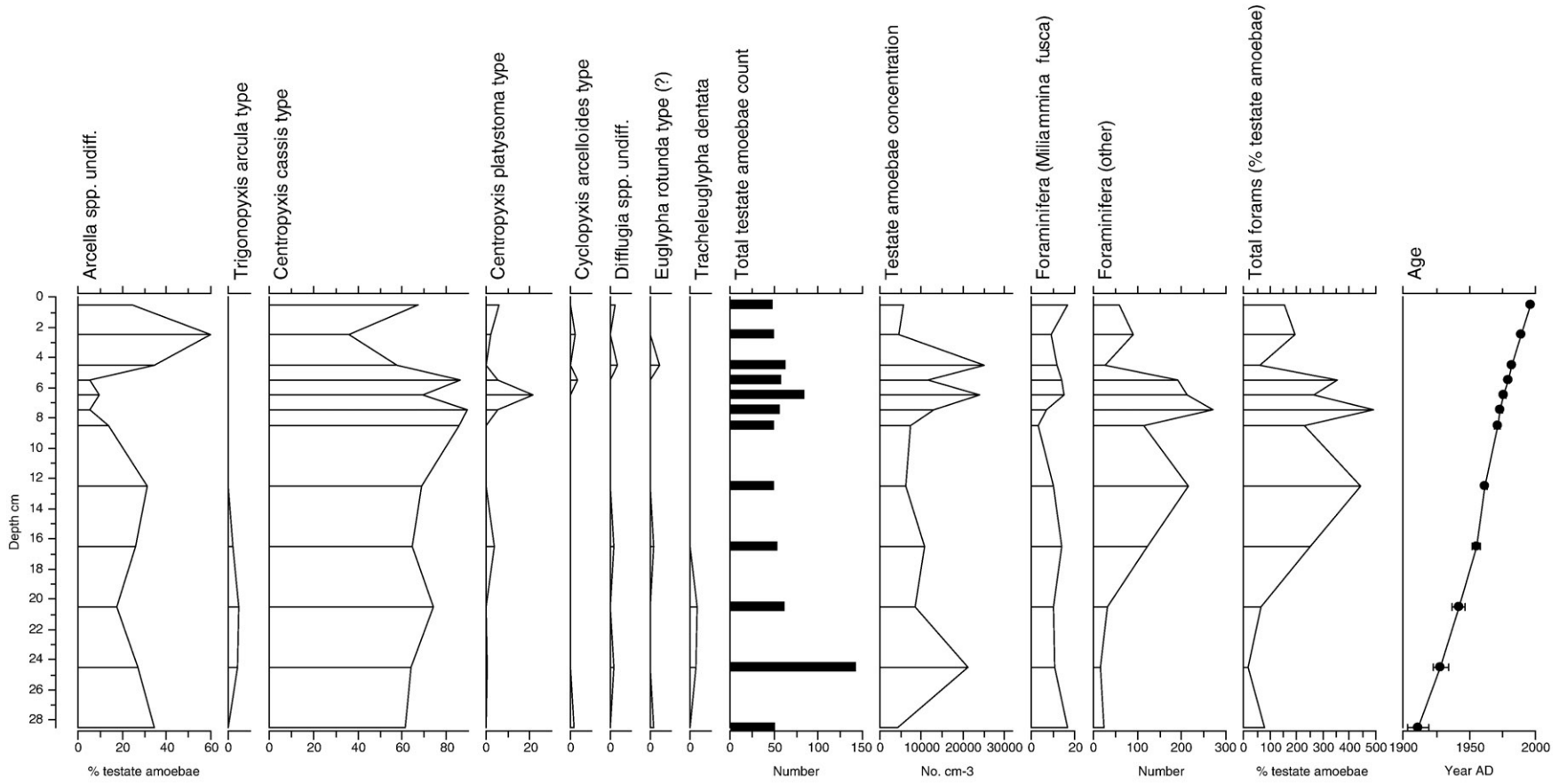


Figure 6. Testate amoebae % diagram from Chezzetcook core CZ-25.

amoebae reconstructions, compared with $1.86 \pm 0.12 \text{ mm yr}^{-1}$ for the tide-gauge data. Although there are a number of issues raised by the testate amoebae data, clear conclusions are difficult given the relatively low sediment accumulation rate and low sample numbers (9 samples from the 20th century for testate amoebae and only 5 for foraminifera).

Chezzetcook

Counts exceeding 50 tests were made down to 29-cm depth, with samples covering most of the 20th century (Gehrels et al., 2005). However, obtaining counts for some of these samples required counting of multiple slides with considerable input of time. Concentrations are similar to those at Wells with numbers up to 25,000 tests g^{-1} but often around 5–10,000 tests g^{-1} (Fig. 6). The assemblages are dominated by *C. cassis* type and *A. catinus* type with lower diversity of minor taxa than at Wells. *C. platystoma* type is more abundant towards the surface and *Trigonopyxis arcuata* type is notable as a high marsh indicator for consistent occurrence in the deeper samples.

The testate amoebae-based reconstructions are very similar to each other. The tolerance downweighted model reduces the amplitude of change by only a small amount and the reconstruction based on the UK data is indistinguishable from the two reconstructions based on North American data (Fig. 7). The overall trend in the testate amoebae reconstructions is very similar to changes inferred from foraminifera, although the gradient in the testate amoebae record is slightly steeper (3.70 ± 0.61 to $4.07 \pm 1.00 \text{ mm yr}^{-1}$ compared to $3.32 \pm 0.43 \text{ mm yr}^{-1}$). The estimated errors for individual samples in both records are very similar ($\pm 5 \text{ cm}$). It is surprising that the errors are so similar, given that the testate amoebae reconstructions are based on data from sites ranging from other parts of the eastern North American coast and the United Kingdom. While we would expect smaller errors for a location with a small tidal range, it is surprising that these very different approaches yield similar error estimates. Reconstructions are in reasonable agreement with the tide-gauge

record, which shows a linear trend of $3.3 \pm 0.11 \text{ mm yr}^{-1}$. Larger short-term fluctuations are shown by the foraminifera-based reconstruction than in the amoebae record. While this may be partly due to the larger number of foraminifera samples analysed, the short-term decline in sea level at ca. AD 1955 registered by the foraminifera is at least partly sampled but not reflected by the testate amoebae record. As this deflection is also not shown by the tide-gauge record, it must be a result of changes only in foraminifera assemblages.

Discussion

Test concentrations and preparation

The data on testate amoebae presented here and other previous studies highlight the problems of separating low numbers of testate amoebae from a matrix of similar-sized particles (Roe et al., 2002). In contrast to terrestrial peat, tests are often present in relatively low concentrations and are obscured by large amounts of silt-sized organic and inorganic detritus. We have attempted to increase the range of samples that can be economically analysed by using a weak alkali treatment in preparation. This has been effective in improving counts to statistically useful levels for the two cores presented here.

While it is well known that strong chemical pre-treatment such as that applied in pollen analysis can selectively destroy tests (Tolonen, 1986; Hendon and Charman, 1997), short periods in weak alkali (5% KOH in this case) do not appear to have this effect. Although further work on a wider range of samples is still needed, the gains in analysis of salt-marsh sediments may outweigh any concerns over loss or damage to tests. Counting of salt-marsh samples is still more difficult than for many terrestrial peat samples and it takes considerable time (typically 0.5–1 day per sample) using multiple slide preparations to achieve counts >50 tests. Some samples will remain impossible to count to these levels, and on the basis of the data from Wells, this limit seems to be around concentrations of 1000 tests g^{-1} . It is not surprising that fossil samples in these cores have relatively low

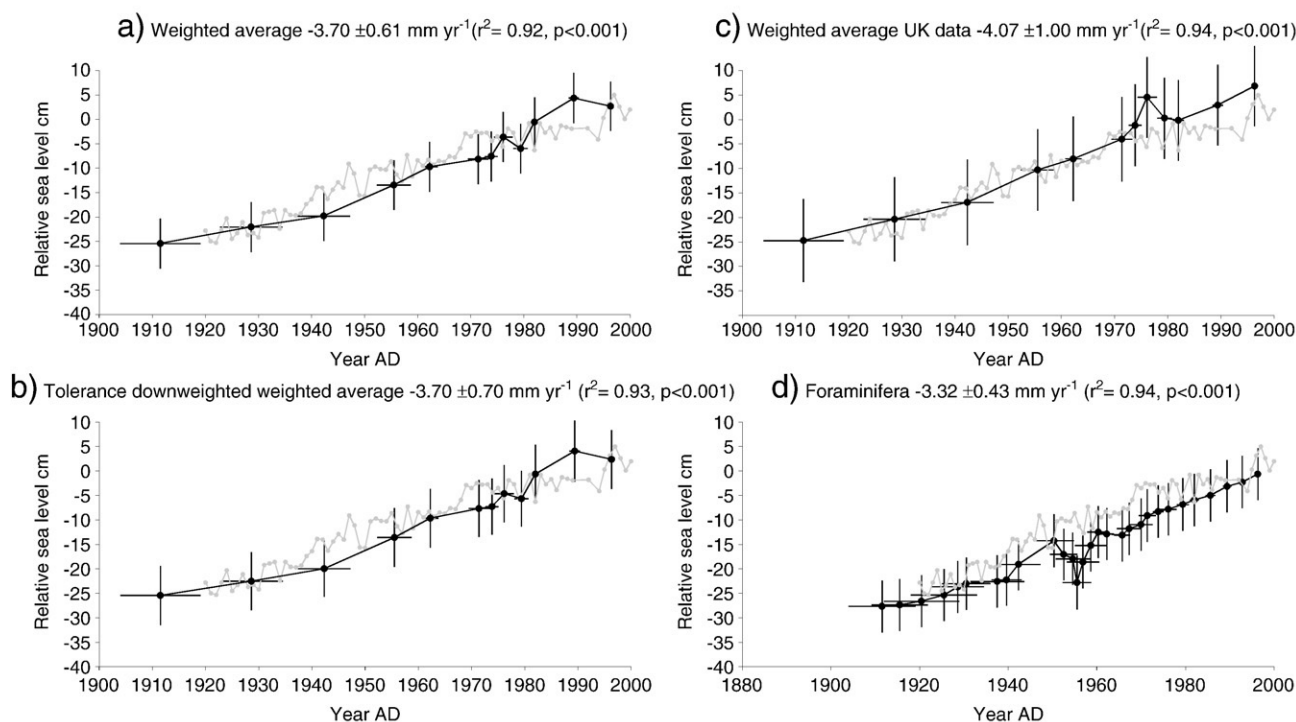


Figure 7. Sea-level reconstructions based on testate amoebae and foraminifera from Chezzetcook Marsh compared to the tide-gauge record from Halifax (grey symbols). The rates of sea-level change are the linear trends over the period covered by the tide-gauge record. For comparison, the linear trend of the tide-gauge record is $3.30 \pm 0.11 \text{ mm yr}^{-1}$. Vertical error bars are RMSEP from transfer functions. Age error bars are 2σ errors from age–depth model.

concentrations because the cores are from the high marsh within the zone dominated by *Balticammina pseudomacrescens* and *Jadammina macrescens*, with low abundances of various other taxa (Gehrels et al., 2002, 2005). The Wells core is from 1.70 m NGVD, which is in the lowermost zone of testate amoebae occurrence (Fig. 2). Testate amoebae are most abundant and diverse above this zone (Charman et al., 1998; Gehrels et al., 2001) so the core location may be sub-optimal for testate amoebae populations. The Chezzetcook core is from just below HAT so is in a better position; this may be one of the reasons why the reconstruction for this site shows greater agreement with the tide-gauge record.

Regional scale transfer functions

The application of the UK training set to modern and fossil North American samples shows that testate amoebae zonation is sufficiently consistent over large regions such as the North Atlantic to be able to use regional-scale transfer functions successfully. Elevations estimated for North American modern samples using the UK transfer function are surprisingly accurate (Table 3, Fig. 3). Reconstructions from fossil samples show very little difference with those based on the North American transfer function (Figs. 5 and 7). This is in contrast to foraminifera, where generally application is limited to local (Gehrels et al., 2001) or regional (Horton et al., 1999b; Edwards et al., 2004) training sets. The wide geographical applicability of the transfer functions suggests that they are more likely to be temporally robust than transfer functions that only perform well in cross-validation for single locations or small regions.

While our data are still relatively few, these results indicate excellent potential for developing large scale regional training sets in future work. Testing transfer functions by application to other regions also reveals some of the problems with relying on cross-validation statistics to evaluate model performance (Fig. 3). While extremely good performance can sometimes be shown for some models such as the PLS model for the UK data (Table 3), problems with systematic bias are clearly revealed when using them to estimate elevations of independent samples with known elevations (Fig. 3). It seems likely that transfer functions that make use of residual variation in each iteration of the calibration calculation (PLS, WAPLS) will be more susceptible to such problems.

Precision and accuracy of reconstructions

One of the main aims in pursuing work on testate amoebae in salt marshes is to improve precision of palaeo-sea level estimates. However, more precise reconstructions must also be demonstrably accurate. Estimated sample-specific errors in fossil samples derived from bootstrapping of the models based on the modern North American data are around ± 5 cm for Chezzetcook and ± 11 cm for Wells, the difference being due to the larger tidal range at Wells. However, these error terms only include uncertainty in the relationship between modern assemblages and measured elevation. They assume the relationship between fossil assemblages and palaeo-elevation is the same, disregarding possible effects of changing tidal regimes, disturbance, taphonomy, preservation and processing and any other factors that may have influenced the observed assemblage. Good agreement between proxies and tide-gauge data in the Chezzetcook sequence suggests that these other effects are small at least for the last 100 yr, and thus we have greater confidence in the envelope of uncertainty at this site (Fig. 7). The agreement is less strong for the Wells site, although low sedimentation rates and consequently low sample resolution make clear conclusions difficult here (Fig. 5). The similarity of error estimates for the UK and North American transfer functions also supports the idea that local site factors play only a relatively minor role in determining testate amoebae assemblages.

An alternative approach to assessing precision is to calculate RMSEP values based on a comparison between the reconstructed values and the tide-gauge data. This yields more realistic error estimates than those based purely on cross-validation. In this case, the RMSEP values are 6.7 cm for the Wells WAT reconstruction and 3.5 cm for the Chezzetcook reconstruction. Surprisingly, the RMSEP values for both cores are lower than the bootstrapped RMSEP values, suggesting the actual error is less than that estimated from the transfer function alone and supporting the idea that bootstrapped errors can be used as a reasonable conservative estimate of the average actual error in reconstructions from the pre-instrumental period. However, it is also clear that some individual samples can yield reconstructed values that are clearly out of line with recorded variations and, if taken at face value in the fossil record, would imply rapid short-term fluctuations in past sea level. Clearly estimates of past sea-level change are more robust for multi-decadal to centennial trends than they are for decadal fluctuations, even where sedimentation rates allow for such high-resolution reconstructions.

Conclusion: improving sea-level reconstructions from testate amoebae

The cores used here for analysis were initially selected to optimise results from foraminiferal analysis. They are within the most stable area of the high salt marsh within the narrow zone dominated by *B. pseudomacrescens* and other high marsh foraminifera. In this zone, foraminifera are abundant at the surface and downcore. However, testate amoebae are most abundant and most clearly zoned in the very uppermost parts of salt marshes (Charman et al., 2002; Gehrels et al., 2006). The fossil assemblages recovered in the two cores presented here are indicative of the mid to lower zones of testate amoebae occurrence in marshes. There are very few of the taxa that are associated with higher locations on the marsh, where zonation of assemblages is better defined because of rapid turnover of taxa along the elevation gradient (Charman et al., 1998, 2002). Coring in locations at higher elevations than would be used for foraminiferal analyses may yield more diverse faunas and perhaps better constrained estimates of past sea levels. The setting of the highest part of the marsh means that these zones are some of the best locations for sea-level reconstruction because they are geomorphologically less dynamic than lower zones. Sedimentation rates are likely to be stable, with continuous sediment accumulation over time. Thus, it is particularly worthwhile pursuing proxy sea-level indicators such as testate amoebae in these locations.

Despite the difficulties with small surface-training sets and sub-optimal core locations, the Chezzetcook record shows that testate amoebae can be used to reconstruct past sea levels with high precision and accuracy. The agreement with both foraminiferal reconstructions and tide-gauge data shows that this technique is promising. The precision of the reconstructed values is approximately ± 5 cm in this microtidal location as assessed by cross-validation of modern training sets and somewhat lower (RMSEP 3.5 cm) when compared with tide-gauge data. This is similar or slightly better than the precision obtained from foraminifera, but this level of precision is unusual for foraminifera studies. Furthermore, the testate amoebae data were from a range of locations on the eastern North American coast and the United Kingdom, suggesting testate amoebae are highly robust against local variations in the species–environment relationships used to estimate past sea levels.

The nominal precision as estimated by cross-validation in the Wells reconstruction is better than that for foraminifera. This is likely due to the macrotidal location where foraminifera zones are less tightly constrained. However, RMSEP values calculated from comparison with the tide-gauge records are slightly higher for testate amoebae than for foraminifera. If the niches of testate amoebae taxa can be better constrained by further studies on surface samples so that

the accuracy of estimates is improved, higher precision estimates of past sea-level change based on testate amoebae analysis will be possible at further sites.

Future studies should retain multi-proxy indicators as a cross-check on the accuracy of reconstructions as well as utilising tide-gauge records alongside high-resolution reconstructions to test reconstruction methodologies. Careful evaluation of transfer functions using approaches other than cross-validation of modern data sets is essential to avoid over-estimating the ability of these techniques to reconstruct past changes from fossil samples. Comparison with tide-gauge records provides a suitable means of achieving this.

Acknowledgments

This paper is a contribution to IGCP Project 495 (“Late Quaternary Land-Ocean Interactions: Driving Mechanisms and Coastal Responses”) and to the North and West Europe working group of the INQUA commission on Coastal and Marine Processes. The paper benefited from the comments of Antony Long and Edward Mitchell in review.

References

- Belknap, D.F., Shipp, R.C., Stuckenrath, R., Kelley, J.T., Borns, H.W., 1989. Holocene sea-level change in coastal Maine. In: Anderson, W.A., Borns, H.W. (Eds.), *Neotectonics of Maine*, Vol. 40. Maine Geological Survey Bulletin, Maine, pp. 85–105.
- Bindoff, N.L., et al., 2007. Observations: oceanic climate change and sea level. In: Solomon, S., et al. (Eds.), *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 385–432.
- Charman, D.J., Roe, H.M., Gehrels, W.R., 1998. The use of testate amoebae in studies of sea-level change: a case study from the Taf estuary, South Wales, UK. *The Holocene* 8, 209–218.
- Charman, D.J., Gehrels, W.R., and Roe, H. M., 2000a. The use of <63 µm fractions in the separation and identification of testate amoebae in the inter-tidal zone. In: Hart, M.B., Kaminski, M. A., and Smart, C. (Eds.), *Proceedings of the Fifth International Workshop on Agglutinated Foraminifera*: Grzybowski Foundation Special Publication, v. 7, p. 89–99.
- Charman, D.J., Hendon, D., and Woodland, W.A., 2000b. The identification of peatland testate amoebae. *Quaternary Research Association Technical Guide*, London.
- Charman, D.J., Roe, H.M., Gehrels, W.R., 2002. Modern distribution of saltmarsh testate amoebae: regional variability of zonation and response to environmental variables. *Journal of Quaternary Science* 17, 387–409.
- Charman, D.J., Blundell, A., Chiverrell, R.C., Hendon, D., Langdon, P.G., 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quaternary Science Reviews* 25, 336–350.
- Donnelly, J.P., Cleary, P., Newby, P., Ettinger, R., 2004. Coupling instrumental and geological records of sea-level change: evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters* 31, art-L05203.
- Edwards, R.J. and Horton, B.P., 2000. Reconstructing relative sea-level change using UK salt-marsh foraminifera. 169, 41–56.
- Edwards, R.J., van de Plassche, O., Gehrels, W.R., Wright, A.J., 2004. Assessing sea-level data from Connecticut, USA, using a foraminiferal transfer function for tide level. *Marine Micropalaeontology* 51, 239–255.
- Gehrels, W.R., 1994. Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, U.S.A. *Journal of Coastal Research* 10, 990–1009.
- Gehrels, W.R., 2000. Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. *Holocene* 10, 367–376.
- Gehrels, W.R., Belknap, D.F., Kelley, J.T., 1996. Integrated high-precision analyses of Holocene sea-level changes: lessons from the coast of Maine. *Geological Society of America Bulletin* 108, 1073–1088.
- Gehrels, W.R., Roe, H.M., Charman, D.J., 2001. Foraminifera, testate amoebae and diatoms as sea-level indicators in UK saltmarshes: a quantitative multiproxy approach. *Journal of Quaternary Science* 16, 201–220.
- Gehrels, W.R., Belknap, D.F., Black, S., Newnham, R.M., 2002. Rapid sea-level rise in the Gulf of Maine, USA, since AD 1800. *Holocene* 12, 383–389.
- Gehrels, W.R., Milne, G.A., Kirby, J.R., Patterson, R.T., Belknap, D.F., 2004. Late Holocene sea-level changes and isostatic crustal movements in Atlantic Canada. *Quaternary International* 120, 79–89.
- Gehrels, W.R., Kirby, J.R., Prokoph, A., Newnham, R.M., Achterberg, E.P., Evans, E.H., Black, S., Scott, D.B., 2005. Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews* 24, 2083–2100.
- Gehrels, W.R., Hendon, D., Charman, D.J., 2006. Distribution of testate amoebae in salt marshes along the North American East Coast. *Journal of Foraminiferal Research* 36, 201–214.
- Gehrels, W.R., Hayward, B.W., Newnham, R.M., Southall, K.E., 2008. A 20th century sea-level acceleration in New Zealand. *Geophysical Research Letters* 35, L02717, doi:10.1029/2007GL032632.
- Hendon, D., Charman, D.J., 1997. The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. *Holocene* 7, 199–205.
- Holgate, S., 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* 34, L01602, doi:10.1029/2006GL028492.
- Horton, B.P., Edwards, R.J., Lloyd, J.M., 1999a. A foraminiferal based transfer function: Implications for sea-level studies. *Journal of Foraminiferal Research* 29, 117–129.
- Horton, B.P., Edwards, R.J., Lloyd, J.M., 1999b. UK intertidal foraminiferal distributions: implications for sea-level studies. *Marine Micropalaeontology* 36, 205–223.
- Juggins, S. 2003 C2 User guide. Software for ecological and palaeoecological data analysis and visualisation. 2003. Newcastle upon Tyne, University of Newcastle.
- Kelley, J.T., Gehrels, W.R., Belknap, D.F., 1995. Late Holocene relative sea-level rise and the geological development of tidal marshes at Wells, Maine, U.S.A. *Journal of Coastal Research* 11, 136–153.
- Patterson, R.T., Fishbein, E., 1989. Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. *Journal of Paleontology* 63, 245–248.
- Roe, H.M., Charman, D.J., Gehrels, W.R., 2002. Fossil testate amoebae in coastal deposits in the UK: implications for studies of sea-level change. *Journal of Quaternary Science* 17, 411–429.
- Rose, N., 2002. Fly-ash particles. In: Last, W.M., Smol, J.P. (Eds.), *Tracking Environmental Change Using Lake Sediments. Developments in Paleoenvironmental Research 2: Physical and Geochemical Methods*. Springer, New York, pp. 319–349.
- Scott, D.B., 1977. Distribution and population dynamics of marsh-estuarine foraminifera with applications to relocating Holocene sea levels. Unpublished Ph.D. Thesis, Dalhousie University, Halifax, Nova Scotia, Canada.
- Scott, D.B., Boyd, R., Medioli, F.S., 1987. Relative sea-level changes in Atlantic Canada: observed level and sedimentological changes vs. theoretical models. In: Nummedal, D., Pilkey, O.H., Howard, J.D. (Eds.), *Sea Level Fluctuation and Coastal Evolution*. Society of Economic Paleontologists and Mineralogists Special Publication 41, pp. 87–96.
- Scott, D.B., Suter, J.R., Kosters, E., 1991. Marsh foraminifera and arcellaceans of the lower Mississippi Delta: controls on spatial distributions. *Micropalaeontology* 37, 373–392.
- Scott, D.B., Hasegawa, S., Saito, T., Ito, K., Collins, E., 1995a. Marsh foraminiferal and vegetation distributions in Nemuro Bay wetland areas, eastern Hokkaido. *Transactions and Proceedings of the Palaeontological Society of Japan* 180, 282–295.
- Scott, D.B., Brown, K., Collins, E.S., Medioli, F.S., 1995b. A new sea level curve from Nova Scotia: evidence for a rapid acceleration of sea-level rise in the late mid-Holocene. *Canadian Journal of Earth Sciences* 32, 2071–2080.
- Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13, 615–621.
- Tolonen, K., 1986. Rhizopod analysis. In: Berglund, B.E. (Ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*, pp. 645–666.
- van de Plassche, O., van der Borg, K., de Jong, A.F.M., 1998. Sea level–climate correlation during the past 1400 yr. *Geology* 26, 319–322.
- Varekamp, J.C., Thomas, E., Van de Plassche, O., 1992. Relative sea-level rise and climate change over the last 1500 years. *Terra Nova* 4, 293–304.
- Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A., Gehrels, W.R., 2008. Evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology* doi:10.1002/joc.1771.