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Deposition times in the northeastern United States during the Holocene: establishing valid priors for Bayesian age models

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Age–depth relationships in sedimentary archives such as lakes, wetlands and bogs are non-linear with irregular probability distributions associated with calibrated radiocarbon dates. Bayesian approaches are thus well-suited to understanding relationships between age and depth for use in paleoecological studies. Bayesian models for the accumulation of sediment and organic matter within basins combine dated material from one or more records with prior information about the behavior of deposition times (yr/cm) based on expert knowledge. Well-informed priors are essential to good modeling of the age–depth relationship, but are particularly important in cases where data may be sparse (e.g., few radiocarbon dates), or unclear (e.g., age-reversals, coincident dates, age offsets, outliers and dates within a radiocarbon plateau).

Here we assessed Holocene deposition times using 204 age–depth models obtained from the Neotoma Paleoecology Database (www.neotomadb.org) for both lacustrine and palustrine environments across the northeastern United States. These age–depth models were augmented using biostratigraphic events identifiable within pollen records from the northeastern United States during the Holocene and late-Pleistocene.

Deposition times are significantly related to depositional environment (palustrine and lacustrine), sediment age, and sediment depth. Spatial variables had non-significant relationships with deposition time when site effects were considered. The best-fit model was a generalized additive mixed model that relates deposition time to age, stratified by depositional environment with site as a random factor. The best-fit model accounts for 63.3% of the total deviance in deposition times. The strongly increasing accumulation rates of the last 500–1000 years indicate that gamma distributions describing lacustrine deposition times ($\alpha = 1.08, \beta = 18.28$) and palustrine deposition times ($\alpha = 1.23, \beta = 22.32$) for the entire Holocene may be insufficient for Bayesian approaches since there is strong variation in the gamma parameters both in the most recent sediments and throughout the Holocene. Time-averaged gamma distributions for lacustrine ($\alpha = 1.35, \beta = 19.64$) and palustrine samples ($\alpha = 1.40, \beta = 20.72$) show lower overall deposition times, but variability remains. The variation in gamma parameters through time may require the use of multiple gamma distributions during the Holocene to generate accurate age–depth models. We present estimates of gamma parameters for deposition times at 1000 yr intervals. The parameters generated in this study can be used directly within Bacon to act as Bayesian priors for sedimentary age models.

1. Introduction

The influx and accumulation of sediment and organic matter into lacustrine and palustrine basins varies over time and space (Holocene: Webb and Webb, 1988; last 150 yrs: Brothers et al.,

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2008). Variations in sediment influx and accumulation rates complicate age–depth modeling, which is essential for correctly reconstructing paleoecological, paleoclimatic and other paleoenvironmental proxies from Quaternary records. The newly-developed Bayesian age modeling tool Bacon (Blaauw and Christen, 2011) combines prior knowledge of local or regional accumulation rates with new information for the record (typically age-controls such as ^{14}C, ^{210}Pb or ^{137}Cs dates, biostratigraphic markers such as the *Ambrosia* rise in the NE United States, or tephra layers) to calculate posterior probabilities of the estimated ages in the record. Bayesian age models are rapidly gaining popularity because they can accommodate non-linear sediment accumulation rates and the irregular probability distributions produced by calibrating radiocarbon dates to calendar years. Bayesian models such as Bacon provide a fundamental improvement over traditional models in that they accommodate the non-normal distributions of most ^{14}C dates and account for the deposition process throughout the record (Blaauw and Christen, 2011). Any age estimates produced by Bayesian methods for a particular record are strongly influenced by both the new information and the prior knowledge, so it is essential to develop estimates of prior knowledge that are well-supported.

Accumulation rates are a key component of the prior knowledge used in some Bayesian age–depth modeling software (Blaauw and Christen, 2005, 2011) although other Bayesian models do not use these data (e.g.: Parnell et al., 2008). A Previous synthesis of Holocene accumulation rates in eastern North American lakes and wetlands reported average accumulation rates of 91 cm/1000 years (Webb and Webb, 1988) but this estimate was based on uncalibrated radiocarbon dates. Given improvements in dating resolution, the addition of new sites, and improvements in radiocarbon calibration, the time is ripe to revisit Webb and Webb (1988) to produce improved estimates for Bayesian models.

Improving age models fundamentally increases our ability to accurately date past events and thus to understand the sequences of past environmental changes. Importantly, better age models also improve estimates of accumulation rates. Accumulation rates are critical to the reconstruction of many proxies such as carbon sequestration in peatlands (Yu, 2011) and past fire events (from charcoal: Marlon et al., 2006; from pollen: Koff et al., 2000). In addition to the value of building better age models, calculating accumulation rates accurately is directly important for Quaternary studies when influx rates for specific proxies are of interest to the researcher. Reliable estimates of uncertainty around accumulation or influx rates are needed for robust multi-proxy analyses of paleoecological or paleoclimate change, especially when examining climatic or ecological events across a number of sites.

Accumulation rates can be controlled by both allochthonous and autochthonous factors and the relative importance of these factors varies considerably among sites and depositional environments. The availability of sediment can be controlled by catchment size, number and discharge of inflow streams, supply of clasts from the catchment, basin size and morphometry, as well as net primary productivity and decomposition rates. The allochthonous and autochthonous variables affecting accumulation may be correlated; they may also be controlled by secondary factors such as temperature and rates of precipitation. Some of the variables affecting accumulation may remain approximately constant through time while others may appear as abrupt unconformities within the accumulation rates of a single site (e.g. changes in the sediment source area: Nederbragt and Thurow, 2001). Sometimes multiple basins may show similar changes in accumulation rate in cases where local processes were controlled by regional changes in climate or vegetation.

As part of a multidisciplinary project aimed at combining paleoecological, paleoclimatic and modern ecological knowledge with statistical and modeling tools to examine interactions among climate, disturbance and vegetation during the past 2000 years in the northeastern United States (PalEON), we synthesized available data on Holocene accumulation rates from relevant sites in the region. Because Bacon requires parameters expressed as deposition time (yr/cm, the inverse of sedimentation rate) we provide new estimates of deposition times based on previously cored lacustrine and palustrine environments from northeastern North America, drawn from the Neotoma Paleoecological Database. We develop a mixed-effects model to show that deposition time varies during the Holocene and we generate estimates of gamma parameters for use by researchers implementing Bayesian age–depth reconstructions in their own research.

2. Methods

Records spanning the Holocene (11,700 to −61 calendar years before radiocarbon 'present', i.e. 1950AD) were assembled for 215 fossil pollen sites from the northeastern United States, a region defined as the PalEON domain (Fig. 1). Age–depth models for eastern North American sites in the Neotoma Paleoecology Database (www.neotomadb.org) were recently examined and revised (Blois et al., 2011), excepting sites with insufficient chronological control. In the reexamined cores, all ^{14}C ages were re-calibrated using the IntCal09 calibration curve (Reimer et al., 2009) and Bayesian change point analysis was used to update poorly constrained sites with new biostratigraphic ages based on the timing of ecological events at high quality sites: *Picea* decline, *Quercus* rise and *Alnus* decline for the late-Pleistocene and early Holocene (Blois et al., 2011), and *Ulmus* decline, *Tsuga* decline, and *Picea* rise for the rest of the Holocene. We used the linear and smooth spline age–depth models generated by Blois et al. (2011) to determine

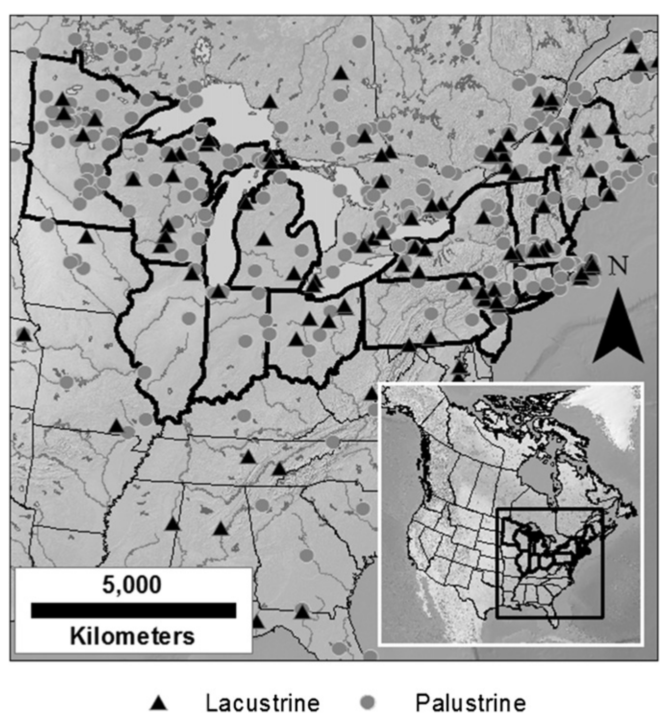

Fig. 1. The PalEON domain (states with heavy lines) includes lacustrine (n = 152; triangles) and palustrine (n = 52; circles) sites. Only sites located within the PalEON domain are used in this analysis. All sites shown in the figure are available from the Neotoma paleoecological database and have newer age–depth models (after Blois et al., 2011).

ages for sampled depths within the cores. A future step will be to revise the age–depth models using Bayesian methods for all sites.

Estimates of gamma parameters representing possible average deposition times (yr/cm) based on prior knowledge are required to calculate age–depth models using Bayesian software such as Bacon (Blaauw and Christen, 2011). These estimates can be based on empirical estimates of the gamma parameters and mean deposition time from previously built age–depth models. Note that because Bacon explicitly relies on deposition time, we focus on that variable here, although accumulation rates (the inverse of deposition time) may be more intuitive to many paleoecologists. To accommodate interest in accumulation rates we also provide results for accumulation rates in supplementary material.

Using the Blois et al. (2011) age–depth models for sites in the northeastern US, we calculate deposition times (yr/cm) and generate a multivariate dataset that includes depth, location (latitude, longitude, elevation), age and depositional environment (Table 1). Deposition time for samples older than 11,700 calibrated years before present (cal yr BP, present being radiocarbon present, at 1950CE) and rates from terrestrial (as defined in Neotoma) and small-hollow depositional environments were removed from the dataset. Deposition times for bogs, fens, mires, marshes and swamps were re-classed as palustrine environments because each class contained too few sample sites for meaningful analysis and since autochthonous deposition is assumed to dominate in each of these environments. We recognize that accumulation processes in these environments differ, particularly between peatland and non-peatland systems. Because of the differences between the processes governing accumulation and sedimentation within these environments, our estimates of deposition time from this grouping must be viewed with some caution. We removed rates equal to or smaller than zero since they represent age-inversions and are considered erroneous. This left 204 sites (152 lacustrine, 52 palustrine sites) and 1102 rate estimates (921 lacustrine, 181 palustrine). This forms a secure subset of sites with sufficient chronological control for analysis.

To assess whether deposition times vary significantly in space and time, we used generalized additive models (GAM) and mixed-effects GAMs (library *mgcv*; Woods, 2011) implemented in R (version 2.13.1; R Development Core Team, 2011). We fit GAMs with thin-plate splines for space and time effects, specifying an underlying gamma distribution with a log link. In the mixed-effects models the sample site is considered the random effect to account for unmeasured variables that might reasonably be site specific. The appropriate smoothing for the splines was determined by minimizing the Akaike Information Criterion of the best-fit model.

$$g(x;\alpha,\beta) = \beta^{\alpha}\frac{1}{\Gamma(\alpha)}x^{a-1}e^{-\beta x} \tag{1}$$

We fit gamma distributions to deposition times in the dataset using the fitdistr function in the MASS package (Venables and Ripley, 2002) for R. Gamma distributions (Equation (1)) have two parameters described using a shape (α) and rate parameter (β; rate is the inverse of scale, θ). Gamma distributions are continuous and positive and appear to match the Holocene deposition time distributions well.

Table 1
Depositional environments for the sites used in this analysis based on site metadata in the Neotoma Paleoecology Database. The dataset is strongly weighted toward lacustrine environments.

Depositional environment		Number of sites
Neotoma data	Re-classed	
Lacustrine	Lacustrine	152
Bog	Palustrine	14
Fen	Palustrine	6
Marsh	Palustrine	6
Mire	Palustrine	20
Swamp	Palustrine	6
Hollow	Removed	4
Terrestrial	Removed	2

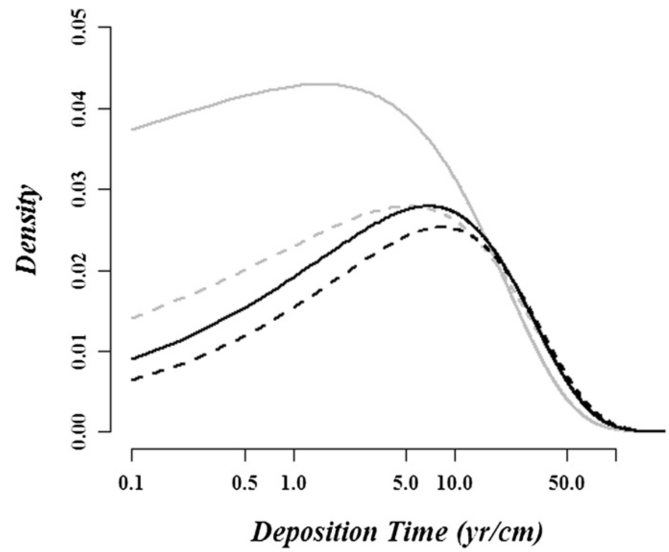

Fig. 2. Gamma density functions describing the probability density functions for deposition times (logarithmic scale) in lacustrine (solid lines) and palustrine (dashed lines) sediments using all samples (gray) and time-averaged parameters (black). Gamma parameters α and β for all curves are reported in Table 3. The bias toward modern sediments in both lacustrine and palustrine sediments results in lower apparent deposition times for both datasets, but these times are higher when deposition times are examined evenly across the Holocene.

The GAM analyses indicate that deposition times vary significantly over time (Results); accordingly we fit moving window (500 yr) estimates of the gamma distribution from the raw data and used these to assess changes in deposition rates over time by constructing 90% confidence intervals for the estimated distributions, as well as estimating mean and median values for the estimated distributions. In all analyses, the gamma parameters were fit using all samples, only lacustrine samples and only palustrine samples. The estimated gamma distributions will help inform Bayesian analyses of age–depth records, either to improve this analysis at a later date, or to improve age–depth models for other records using software such as Bacon (Blaauw and Christen, 2011).

3. Results

3.1. Data summaries

Deposition times within the dataset ranged from 0.28 to 301 yr/cm (one outlier, 0.17 yr/cm, was removed), with a median time of 13.2 yr/cm and a mean of 21 yr/cm. The median and mean accumulation rates are 0.076 cm/yr and 0.14 cm/yr respectively. Our estimates compare well to the Webb and Webb (1988, hereafter WW) accumulation rates for historic (last 350 cal yr BP) and Holocene (350 cal yr BP < ages < 11, 700 cal yr BP) accumulation rates compare well. The mean Holocene rates calculated here (x_{Holocene} = 78 cm/ka) are slightly lower than the WW Holocene rates (x_{Holocene} = 81 cm/ka) but well within the standard deviation. However, the median rate for Holocene accumulation is much lower (this paper: 67 cm/ka versus WW: 56.34 cm/ka) indicating the addition of few very high accumulation rates, but a large number of samples with very low accumulation rates. Mean historic accumulation rates are slightly higher in the new dataset, but again within the WW standard deviation (this paper: 306 cm/

ka versus WW: 298 cm/ka) while the median is almost equal (this paper: 222 cm/ka versus WW: 222 cm/ka).

Gamma probability distributions suggest that lacustrine samples have a lower mean deposition rate (faster sediment accumulation) than the palustrine samples. Palustrine environments generally have higher deposition rates (Fig. 2) and higher variability in deposition times, likely reflective of the diverse systems (e.g., marshes, swamps, peatlands) included in this category. The similarity between the gamma parameters for lacustrine and all sites is largely due to the fact that lacustrine samples make up 70% of the total samples in the dataset.

The lacustrine dataset has a greater proportion of recent (age $<$ 1000 cal cal yr BP) samples ($n = 382$; 38%) than the wetland dataset ($n = 43$; 18%) (Fig. 3). This may result from researcher preferences in sampling both long and short Holocene records, including post-settlement records, from lacustrine sites while preferring entire Holocene records from wetlands such as bogs or swamps. It is well known that recent samples will have shorter deposition times because these upper sediments have been less compacted, and this is seen in the current dataset.

A mixed-effect GAM using site as a random factor accounts for 44% of the total null model deviance. When spatial variables (longitude, latitude and elevation) are included in the mixed-effects GAM they fail to improve the model relative to the null mixed-effects GAM (Table 2). This indicates that the deviance explained by spatial variables is likely to be an expression of site-level characteristics rather than explicitly spatial processes.

Age was a significant predictor of deposition time: a mixed-effects GAM predicting deposition time using site as a random effect with age as a thin-plate spline factored by depositional environment (lacustrine versus palustrine) and excluding depth was able to capture 63.3% of the deviance within the dataset. The model could be improved further by adding depth as a variable, however depth and age are highly correlated. Indeed the GAM produces a depth model that violates the expectations of a monotonic relationship between depth and deposition time resulting from compression within the sediment core, assuming sediment composition remains somewhat constant through time. This relationship is likely to require a physical model using site and sediment specific parameters that are unavailable to us at this time.

Time series of the modeled deposition time for the mixed-effects GAM (Fig. 4) show that lacustrine deposition times decrease rapidly from 12,000 to ~10,500 cal yr BP, at which point deposition times stabilize, fluctuating, but declining slowly to 2000 cal yr BP. Deposition times for lacustrine sediments increase

Table 2
All samples, percent deviance explained by the parameters in a generalized additive mixed model predicting deposition time either alone or using site as a random effect. All results are significant when tested using an anova against the null model in the first row of their respective column except when noted by n.s.

Variable Type	Deviance explained		
	Variable alone	Conditioned by depositional environment	
		Alone	With random effect
Null	0	1.5	44
Age	29.6	31.5	63.3
Depth	6.97	9.39	57.7
Longitude	7.04	9.66	$43.9^{n.s.}$
Latitude	4.01	7.03	$44.1^{n.s.}$
Altitude	3.85	9.22	$44.0^{n.s.}$

at 2000 cal yr BP, reaching a peak at 1000 cal yr BP (i.e., the slowest accumulation rates) and then declining sharply to a minimum in the most modern sediments. Palustrine rates appear to be largely stable throughout the Holocene until 2000 cal yr BP. Palustrine deposition rates decline strongly at 2000 cal yr BP, to a minimum in the most modern sediments where the deposition rate is slightly higher than in lacustrine sediments. There is no apparent relationship between lacustrine and palustrine deposition times during the Holocene except during the last 500 years. However, the large uncertainty in the palustrine model may mask connections.

3.2. Gamma distributions

The modeled changes in deposition times during the Holocene (Fig. 4) are reflected in changes to the median and mean deposition rates (Fig. 5) when data are analyzed using a 500 year moving window.

The 90% confidence intervals from the estimated gamma distributions are large for both sediment types, but it is possible to observe two patterns in the median and mean deposition rates over time (Fig. 5). A quasi-periodic pattern of phase-changes from high to low deposition is visible in palustrine depositional times. The increases in median and mean deposition times for palustrine samples appear to have a periodicity of ~3500 years with peaks at ~8000, 5500 and 2000 cal yr BP. Although the variability in lacustrine sediments is much lower, a less extreme pattern of changing deposition times is apparent. Lacustrine sediments have higher and more variable deposition times in the early and mid-Holocene and a steep decline in the last 1000 years. The last millenium is a time when α for palustrine deposition times is increasing, reflected in the rapid drop in

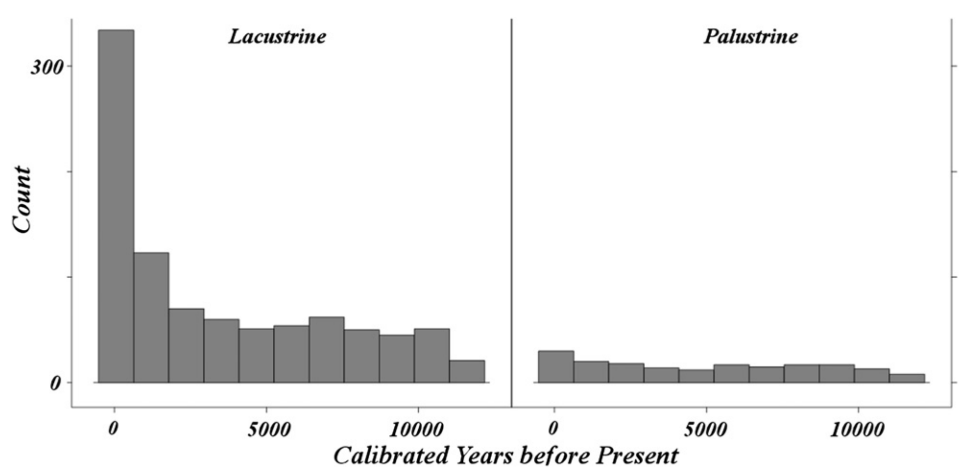

Fig. 3. The distribution of ages for deposition rates within lacustrine and palustrine samples for the dataset. Lacustrine samples have greater data coverage in the younger sediments than palustrine samples.

Table 3
Gamma parameters for 1000 year intervals during the Holocene. The parameters for 'All Samples' are estimated directly from the dataset with no age control. The time-averaged parameters are estimated from the fitted distributions for each 1000-year time interval, removing the sample bias toward younger-aged sediments.

	Lacustrine		Palustrine	
	Alpha	Beta	Alpha	Beta
All Samples	1.08	18.28	1.23	22.32
Time-Averaged	1.35	19.64	1.40	20.72
0 cal yr BP	0.94	14.98	1.78	5.64
1000	1.72	12.65	1.65	20.49
2000	1.85	10.76	2.05	15.79
3000	1.76	11.50	2.08	11.55
4000	1.32	17.42	2.94	9.65
5000	1.70	15.87	1.49	28.25
6000	1.54	17.14	0.91	42.04
7000	2.60	8.04	3.54	4.03
8000	2.78	10.17	1.32	30.36
9000	2.11	10.45	0.89	45.28
10,000	2.01	17.91	4.15	5.18
11,000	0.90	62.98	2.33	11.61

deposition times. Some of the variability in the parameters for the palustrine sediment results from the small number of samples in each time bin. However sample size and α show no significant relationship ($r = -0.21$, $p > 0.05$) in the palustrine dataset.

The α and β parameters of the gamma probability function are negatively correlated for lacustrine ($r = -0.51$, $p = 0.01$) and palustrine deposition times ($r = -0.67$, $p < 0.001$) as might be expected in a gamma function.

4. Discussion

Estimating accurate age–depth models and quantifying temporal uncertainty is essential for all aspects of paleoclimatic and paleoecological research. Our analyses of deposition times in the northeastern US contributes toward the application of Bayesian age models by providing a comprehensive table of estimated gamma parameters that can be used directly by researchers applying modern age–depth modeling software (e.g., Bacon) that require informed priors to model sediment accumulation rates. Although the results shown here are for a relatively limited spatiotemporal domain (northeastern US during the Holocene), the fitted gamma parameters may serve as a first approximation for other northern temperate lacustrine and palustrine environments. This approach to establishing priors can also be applied for other regions and time periods with large datasets of previously collected and dated sediment. Future efforts should focus on the separation of wetland types to establish more appropriate priors for these diverse depositional settings.

The use of these estimated gamma parameters in recalculating Bayesian age–depth models for sites in the northeastern US may produce some circularity. However, because a large number of sites are used for parameter estimation, no single site should have undue influence on the overall estimates, minimizing circularity when estimates are applied to recalculate age models for individual sites. Moreover, only 'stable' sites were considered for this analysis and a wide window (either 500 or 100 years) was chosen to calculate the gamma parameters. Of course, the application of these parameters to any new sites (i.e. sites not included in the estimation dataset) should be entirely free from circularity.

This analysis quantifies variability in deposition times and accumulation rates among sites and across time, driven by physical processes associated with deposition and compaction within the sediment column and perhaps also by recent human activities. Accumulation rates appear to be increasing over the last 150 years in European and North American lakes (Brothers et al., 2008; Rose et al., 2011), and over the last 300 years in degrading lake systems in Japan (Ahn et al., 2006) possibly as a result of human influence. Our analysis reveals decreasing deposition times over the last 1000 years, but the causes are obscure. Brothers et al. (2008) indicate that accumulation rates over the last 150 years are spatially structured in eastern North America. We find no evidence of spatial structure at longer time scales that cannot be attributed to the random effects associated with the distribution of sample sites in the dataset (Table 2), but this may be an effect of the availability of site-specific data for basin and watershed size, sediment-type and other variables that might affect deposition times.

The results of Webb and Webb (1988) appear to be relatively robust across the Holocene when radiocarbon corrected data are examined. Webb and Webb (1988) show a pattern of declining accumulation rates during the Holocene when radiocarbon ages are calibrated. Using a larger dataset and Intcal09 radiocarbon calibration we show a much sharper decline in accumulation during the last 500–1000 years, and reveal more pronounced periodicity in variation for both lacustrine and palustrine sediments when the gamma parameters are examined (Figs. 4 and 5).

It is not clear why the fitted gamma distributions for palustrine environments change so strongly during the Holocene, and

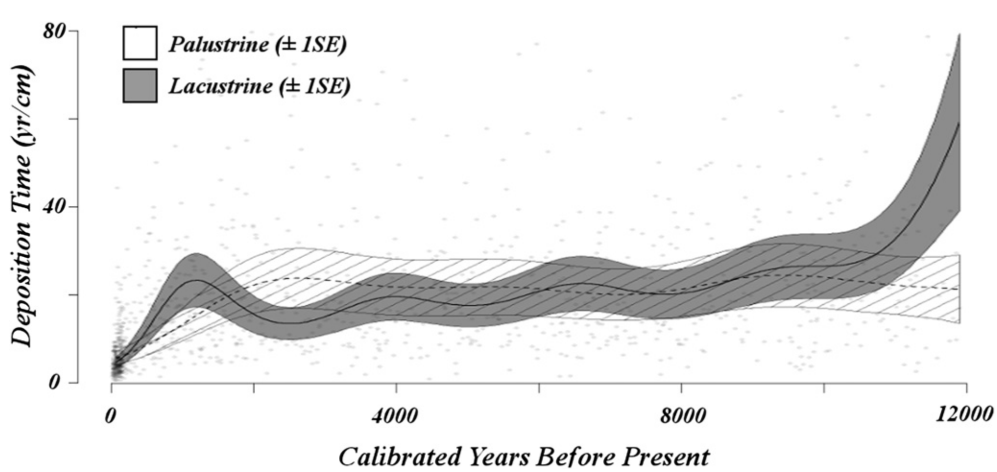

Fig. 4. Modeled response of deposition time with age using a random effects model stratified by depositional environment. Results here are shown for one site (Aino Pond), but with both predicted palustrine and lacustrine responses with age. Other sites would show similar trends, shifted up or down depending on the random effect. Shaded regions represent one standard error. Actual deposition times from the dataset are represented as shaded points. Points with sedimentation rates greater than 85 yr/cm ($n = 37$) were omitted from the graph for clarity but are included in the analysis.

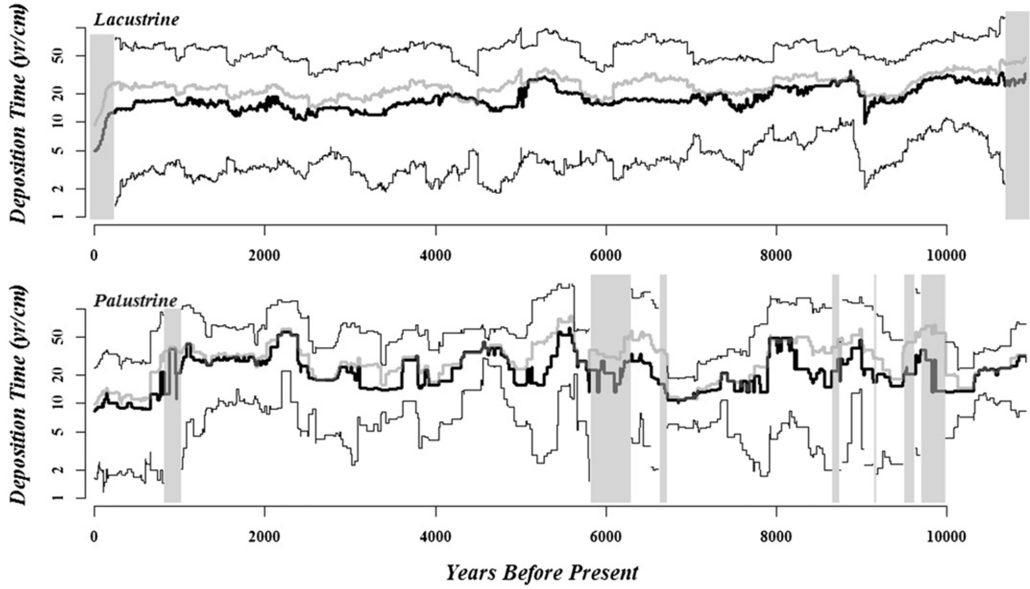

Fig. 5. Change in median (thick black line) and mean (thick gray line) deposition times during the Holocene for lacustrine and palustrine sediments estimated from gamma distributions fit to a 500 year moving window of deposition times for lacustrine and palustrine sediments. The graphs show the 90% confidence intervals (thin line) for deposition times. Gray bands represent regions where confidence statistics could not be generated for the estimates due to small sample sizes.

whether this is a real signal or random fluctuations. At this time we regard the apparent variations in palustrine sedimentation at a 3500 year cycle as an interesting pattern worthy of further study, but potentially an artifact of uncertainty in the palustrine data since the pattern (Fig. 5) does not appear to be significant in the GAM model (Fig. 4).

Accumulation rates have been tied to climatic phenomena in the Cathedral Mountains of British Columbia (Evans and Slaymaker, 2004), where increased sediment yield rates in tree-line lake basins is related to reduced vegetation cover as a result of cooler climates. Evans and Slaymaker (2004) indicate the strong role of local basin dynamics in controlling sediment yield, and note that not all basins in the region show patterns similar to those of the tree-line lakes. Although the temporal patterns of change in deposition times are not particularly indicative of strong climate forcings, the distributions of gamma parameters for both lacustrine and palustrine sediments do indicate both short term and longer term changes in the distributions of accumulation rates, potentially indicating climatic linkages.

5. Conclusions

This paper summarizes and quantifies our prior knowledge of Holocene deposition times in the northeastern US in a form that can be readily applied by users of Bayesian age models. Mixed-effects models suggest that deposition times vary significantly over time and from site to site, but with no evidence for significant variations across latitude, longitude or altitude.

We hope that the use of these gamma parameter estimates will improve age–depth modeling in the region, and also spur the development of other regional datasets that can serve as a strong base of prior knowledge to inform Bayesian (and other) age models.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.quascirev.2012.05.019.

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