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Holocene hydroclimate stability in three lake sediment records from the southeastern United States

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ABSTRACT

Many Holocene paleoclimate records from the southeastern United States (SE US) have limited chronological constraints and/or low sedimentation rates and consequently low resolution; this presents challenges in discerning the relative importance of synoptic–scale drivers of past hydroclimate. In this study we summarize three lake sediment records that are uniquely located to test hypotheses regarding the importance of the Pacific North American (PNA) pattern and the North Atlantic Oscillation (NAO) over the last 5000 years. At Pigeon Marsh, Buck Pond, and Halls Pond, we used sedimentological (radiocarbon dating of transect cores), physical (grain size), geochemical (carbon and nitrogen ratios and isotopes), and biological (palynomorphs) proxies to reconstruct lake level and lake environment. Moderate lake and environmental changes occur around 2000 cal yr BP at Buck and Halls Pond, which is regionally consistent with other paleorecords and may suggest that the NAO was an important control. However, our results generally indicate fairly stable hydroclimate conditions up until historical European settlement when land clearance caused vegetational and lake hydrologic balance changes that were unprecedented in both magnitude and rate compared to the middle/late Holocene.

1. Introduction

Rising global temperatures are expected to result in a 3 to 4 °C increase in annual temperatures in the southeastern United States (SE US) but estimates of future changes in precipitation are highly variable (Easterling et al., 2017; Mulholland et al., 1997). The lack of understanding regarding the drivers of hydroclimate variability is a profound vulnerability in the planning for future climate change. This hampers our ability to make predictions which has economic consequences: in the southeast climate region, drought in 2012 resulted in a CPI-adjusted total of $40.5 billion in US economic losses and flooding in 2010 resulted in $3.2 billion in losses (NOAA/NCEI, 2019). The uncertainty associated with future precipitation patterns is, in part, because of the changing nature of the relationship between temperature and precipitation in the SE over the 20th century (Portman et al., 2009).

Records of past climate can provide insight into this relationship prior to the 20th century, and tree ring growth bands have been instrumental in understanding this relationship over the past several hundred years (Cook et al., 2007; Stahle and Cleaveland, 1994, 1996). However, an investigation of these patterns over longer timescales is advantageous and permits a centennial–scale understanding of climate cycles and variability. In the SE US, there are a limited number of well–dated, multi–proxy, paleoclimate records focused on Holocene precipitation, which has been highlighted as a major knowledge gap in a synthesis of North American hydroclimate (Rodysill et al., 2018). Consequently, there is a pressing need to develop paleorecords of hydroclimate across the understudied SE US to investigate its spatiotemporal variability in the Holocene.

Past paleoclimate studies have proposed several mechanisms to be important in controlling SE US hydroclimate. For example, the North Atlantic Oscillation (NAO) influences the strength and position of the Bermuda–Azores high and Icelandic low (Rodgers, 1984). During an NAO+ phase, the pressure difference between the high and low is stronger, the high is in a northerly location (Liu and Fearn, 2000), and more hurricanes are directed up the Atlantic coast (Scott et al., 2003) which decreases moist air flow into the Gulf states; vice versa for an NAO− phase. Additionally, some researchers have proposed that the Atlantic Multidecadal Oscillation (AMO), the 60–to–80–year cycle of sea surface temperature variability in the Atlantic (Kerr, 2000), has an impact on SE US hydroclimate wherein a positive anomaly causes

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decreased precipitation (Knight et al., 2006). Evidence for such a trend beyond the historical record may have been observed in a speleothem from northern Alabama (Aharon and Dhungana, 2017). However, the relative importance and impact of the NAO, AMO, and other mechanisms on surficial water availability is unclear.

In this study, we summarize three lake sediment records with the intent of understanding what synoptic–scale climate patterns drive centennial–scale hydroclimate variability in the SE US over the last 5000 years. We focus on this period because relative changes in sea level are <0.6 mm/yr (Milliken et al., 2008) and therefore minimal enough to not disproportionately affect groundwater and thereby lake levels. Additionally, several synoptic–scale climate drivers (such as the NAO) switch phase at different times during the last 5000 years. Of particular interest to this study, the Pacific North American (PNA) pattern influences precipitation, temperature, and storms tracks across the US and manifests itself as either anomalous ridging or troughing pressure configurations which are enhanced in the cold season. The PNA is an important influence on the hydroclimate of the Midwest and SE US, therefore we hypothesized that when the PNA switched from a negative to positive phase approximately 4000 cal yr B.P. (Liu et al., 2014), there would be an observable change in lake hydrologic balance.

To test this hypothesis, we targeted three lakes in regions of the SE US that have opposing hydroclimate responses to the PNA, and used radiocarbon dating of transect cores, grain–size distributions, carbon to nitrogen ratios (C/N), and the stable isotopic composition of organic matter ($\delta^{13}C$, $\delta^{15}N$) to infer changes in lake hydrologic balance driven by changes in precipitation. We acknowledge that these proxies are not unambiguous indicators of hydroclimate. For example, low C/N ratios indicate a more aquatic source of organic matter while high ratios indicate a more terrestrial source (Meyers, 1994). While these ratios broadly suggest depositional setting, there are additional controlling factors such as primary productivity and land use change, which can sometimes be disentangled with the use of carbon and nitrogen isotopes (Brenner et al., 1999; Hodell and Schelske, 1998). In a complementary manuscript we used palynology to reconstruct estimates of mean annual precipitation and temperature using Climate REconstruction SofTware (CREST) (Chevalier, 2022) and additionally examined fossils of fresh–-water algae (Smith et al., 2023). In that manuscript we found little evidence for large magnitude changes in climate from the middle Holocene to present–day. However, many vegetation types in the SE US may be insensitive to all but substantial changes in temperature and precipitation (Goman and Leigh, 2004; Spencer et al., 2017); therefore, we sought to either support or refute our interpretations with additional physical and geochemical evidence.

2. Background

2.1. Study locations

The climate of the SE US is characterized by warm average annual temperatures with a maximum monthly temperature of 23.2 °C in August and minimum monthly temperature of 5.5 °C in February from 1974 to 2017 (Lawrimore et al., 2011). Annual precipitation is around 1500 mm (from 1974 to 2017) (Lawrimore et al., 2011) and most large rainfall events occur in the winter/early spring (Keim, 1996) (Fig. 1A). These events are controlled, in part, by geopotential height anomalies set up by the ridging and troughing patterns of the PNA during the cold season (Liu et al., 2014). During PNA+ phases, more intense rainout from Gulf moisture sources occurs, causing increased precipitation along the Gulf Coast states (Liu et al., 2014). During PNA− phases, increased moisture flux from the Gulf region penetrates further into the continental US, creating the observed dipole within the SE. Precipitation during winter/early spring (DJFM) has a + 0.4 correlation with the PNA index in the south and a − 0.4 correlation in the north, demonstrating that the PNA is an important driver of seasonal precipitation (Fig. 2A).

Connected to PNA variability is the El Niño Southern Oscillation (ENSO) (Liu et al., 2017), a reversal of the normal easterly winds of the Walker circulation in the Pacific. As a teleconnection, El Niño phases have implications for North American atmospheric circulation and result in a southerly shift of the subtropical jet which causes increased precipitation in the SE US (Seager et al., 2006) (Fig. 2B); vice versa for La Niña phases. ENSO cycles are short–lived with a 5–to–7–year cycle, but

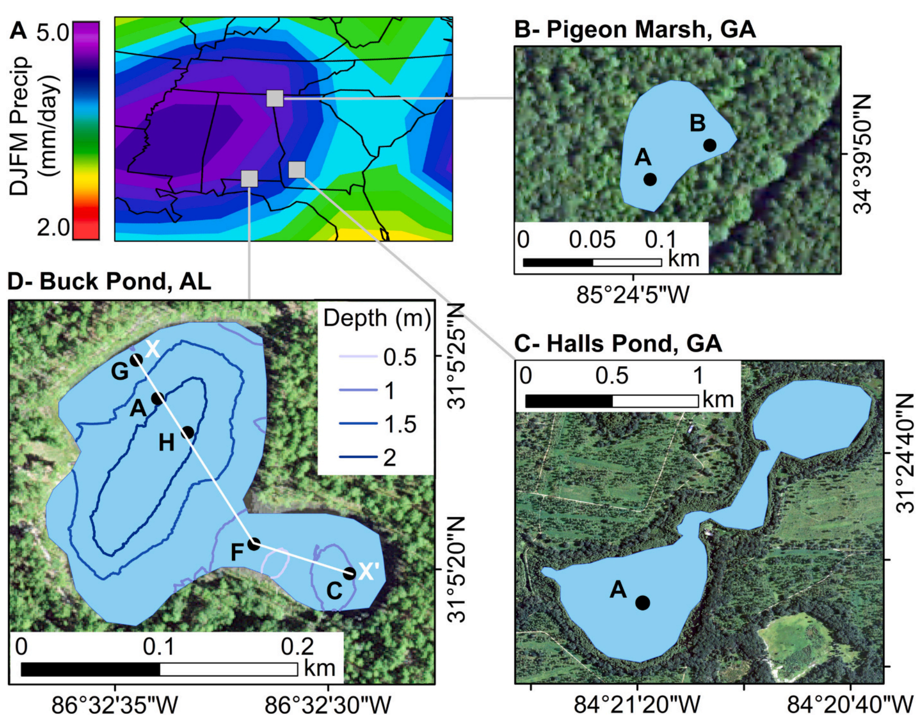

Fig. 1. A) Global Precipitation Climatology Project (GPCP) average (mm/day) for December, January, February, March 1980–2022. Image provided by the NOAA/ ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/. Study sites denoted by gray boxes. B) Pigeon Marsh, GA with coring sites. C) Halls Pond, GA with coring sites. D) Bucks Pond, AL with coring sites along transect X–X' and 0.5 m depth contour intervals.

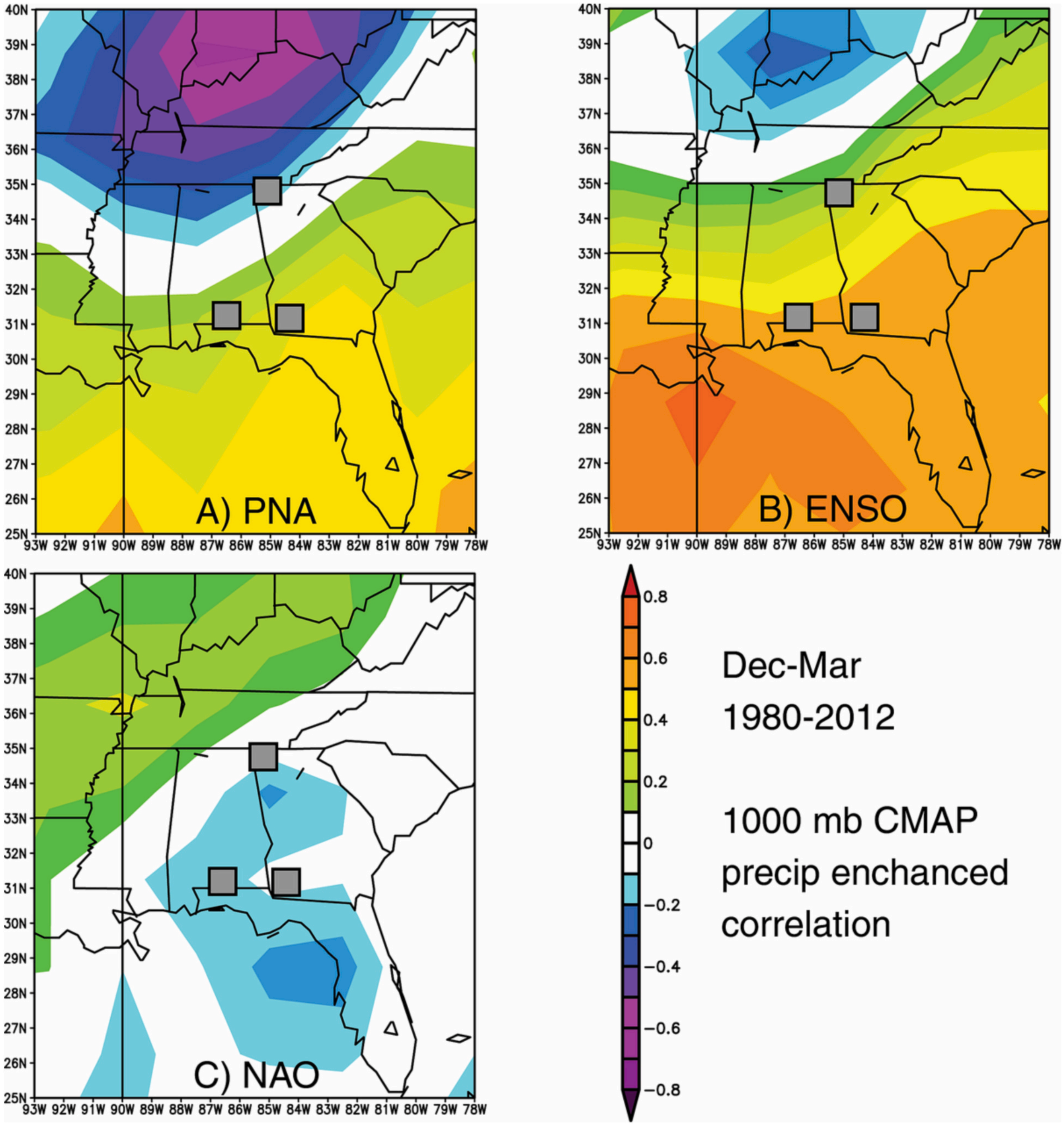

Fig. 2. December, January, February, March 1980–2012 1000 mB CMAP precipitation (enhanced) correlation coefficient with A) Pacific North American pattern, B) multivariate ENSO index, and C) North Atlantic Oscillation. Image provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at http://psl.noaa.gov/. Study sites denoted by gray boxes.

millennial– and centennial– scale trends in ENSO frequency and intensity change the mean–state of precipitation and temperature as summarized by Lu et al. (2018). Given the high temporal resolution necessary to discern the impact of individual ENSO events, in this study we only consider ENSO in the context of its influence on the PNA. Lastly, as previously described, the NAO influences the storm track of hurricanes into the Atlantic or Gulf coasts, thereby playing a role in the delivery of large magnitude, event–based precipitation.

Our primary objective with this study was to test the influence of the PNA on the hydroclimate of the SE US in the late Holocene. On the basis of different expressions of synoptic–scale climate drivers on hydroclimate, we chose three lakes that were suitable: Pigeon Marsh in northwestern Georgia (34°39′50"N, 85°24′4"W, 540 m asl) (Fig. 1B), Halls Pond (31°24′14"N, 84°21′22"W, 50 m asl) in southwestern Georgia (Fig. 1C), and Buck Pond (31°5′22"N, 86°32′34"W, 70 m asl) in southeastern Alabama (Fig. 1D). The sites receive similar amounts of DJFM precipitation (Fig. 1A) but are located such that there are differences in the impact of the PNA, ENSO, and NAO (Fig. 2). Since the PNA and NAO have switched phases in the late Holocene and have different expressions in our study site regions, we can test which climate driver was most closely linked to changes in hydroclimate as archived in lake sediment records. We did not expect to observe the AMO in our records since it has 60–to–80–year cycles (Kerr, 2000) and the sedimentation rates at the study sites were not fast enough to permit such temporal resolution.

Buck Pond, AL is a small (0.027 km^2) sinkhole pond in the Conecuh National Forest with a maximum depth of 2.3 m and an average depth of 1.5 m (Fig. 1D). The catchment area is 2.1 km^2 and composed of undifferentiated Miocene aged sands and clays (Horton et al., 2017). While the catchment has been a national forest since 1936, prior to its acquisition, it was logged almost completely for timber (Pasquill Jr., 2023). Buck Pond has two small inflowing streams and one outflow to the adjacent Ditch Pond. Halls Pond, GA (Fig. 1C) has two basins for a combined area of 0.63 km^2. This study focuses on the southern basin which has a maximum depth of 1.8 m. The catchment (area = 1.645 km^2) is entirely composed of Ocala limestone (Horton et al., 2017) and the lake formed as a karst sinkhole. Since 1850, the surrounding land has functioned as first a plantation, later a sharecropping system, and presently a hunting preserve (US National Park Service, 1989). Pigeon Marsh, GA (Fig. 1D) is a small (0.003 km^2) and shallow marsh with a maximum depth of ~1.0 m. The marsh likely originated as a karst sinkhole in the underlying and adjacent Mississippian limestone (Horton et al., 2017). The catchment area is 0.044 km^2 and composed of undifferentiated Pennsylvanian conglomerate, sandstone, and shale (Horton et al., 2017) with DeKalb stony loam soils (McLendon, 1910). Prior to the 1930s, the land was used for agriculture and had been logged. However, the water table dropped in the 1930s, agriculture ceased, and secondary growth forest predominated with the eventual leasing of the land by the state in 1969 (Georgia Conservancy, 1998).

2.2. Previous studies

Numerous previous studies on the late Quaternary paleoclimatology of the SE US were conducted by Delcourt, Delcourt, and Watts in the 1970s and 80s as summarized in Watts (1980b). These studies focused primarily on palynological assemblages as archived in lake sediments. During the Last Glacial Maximum, estimated to be expressed in the SE US from 23,000 to 13,500 cal yr B.P. (Watts, 1980b), conditions were generally dry and cool (Watts, 1980a; Watts et al., 1992), although there is some evidence to suggest that warm conditions persisted along the Gulf region (Delcourt et al., 1983; Delcourt, 1980). The timing of the deglacial transition into wetter conditions generally starts in the early Holocene in more northern sites and later in more southern sites; this may be due to the influence of eustatic sea level fall on the local water table (Watts, 1971).

At Pigeon Marsh, Watts collected 93 cm of sediment and two radiocarbon dates indicated that the entire Holocene was encompassed in the upper ~80 cm. Palynology recorded the deglacial transition into a wetter climate followed by a drier one in the early Holocene. However, due to limited chronological constraints as well as the potential, but untested, possibility of sediment hiatuses, it was acknowledged that the timing and duration of these transitions was unknown. Most of these early studies focused on the deglacial transition because of short sediment sequences in the Holocene. However, there were some studies that detected vegetational change in the Holocene, most prominently around 5000 cal yr B.P. when coastal–plain forests became replaced by pine forests which were more resistant to fire and possibly reflected an increase in hurricane frequency (summarized in Delcourt and Delcourt, 1985). Jones and Singletary Lakes, NC also record this vegetational change (Lane et al., 2018) and there, the use of hydrogen isotopes of n-alkanes allowed the authors to conclude that there was no change in evapotranspiration at this time. The authors suggested that this ecological change may be attributable to indigenous human landscape management.

This previous work gives a general picture of late Quaternary climate and provides a foundation upon which this study is built; however, there were several limitations of the earlier work. Chronology was constrained using only bulk sediment radiocarbon dates, many of which spanned 10 cm or more (Delcourt et al., 1983; Delcourt, 1980; Watts et al., 1992), integrating ages from a mixture of materials over wide intervals. The spacing of these radiocarbon dates down core was also very sporadic, making the date of transitions completely unknown. Additionally, analyses in these previous studies relied almost exclusively on low–resolution sampling, as wide as 20–50 cm sampling intervals.

Additional context for SE US Holocene hydroclimate comes not from lakes, but from several speleothem records, which archive the oxygen isotopic value of precipitation. In the SE US, the oxygen isotopic composition of precipitation is primarily controlled by the balance between summer and winter sourced precipitation. For example, at DeSoto Cave in northern AL, the authors inferred a gradual switch from winter to summer dominated rainfall with notable drought events from 5200 to 4700 and 2000 to 1700 cal yr B.P. (Aharon et al., 2012; Aharon and Dhungana, 2017). War Eagle Cave, also from northern AL, identified a similar change in the seasonality of rainfall with notable increases from 12,000 to 11,000 cal yr B.P., at 8200 cal yr B.P., and from 1200 to 400 cal yr B.P. (Medina-Elizalde et al., 2022). In both studies, the authors linked the Holocene– and centennial–scale trends to a slowing of the Atlantic Meridional Overturning Circulation and southward displacement of the Intertropical Convergence Zone, bringing more precipitation to the SE US. On decadal timescales, Aharon and Dhungana (2017) suggested links with the AMO wherein a positive or warm phase caused dry summers and vice versa for a negative or cold phase.

3. Materials and methods

3.1. Core collection

At Buck Pond, cores were collected from 5 locations in 2018 and 2021 at a variety of water depths using a Livingstone corer (Fig. 1D) (Wright et al., 1984). Cores were collected in 1 m sections with 20–30 cm of overlap and correlated based on stratigraphy. Cores that preserved the sediment–water interface were collected using a lightweight percussion coring system at two locations (A and C). These cores were sliced in the field at 0.5 cm intervals and used for ^{210}Pb dating and other analyses. At Halls Pond, cores were collected in 2017 from the depocenter of the southern basin (water depth of 1.8 m) (Fig. 1C). A core that preserved the sediment–water interface was collected and sliced in the field at 0.5 cm intervals and was overlapped with one core from a Livingstone corer. The overlapping section was correlated based on stratigraphy and loss–on–ignition 550 °C. At Pigeon Marsh, multiple overlapping cores were collected from 2 locations in 2021 at water depths of 0.3 m (A) and 0.9 m (B) using a Livingstone corer (Fig. 1B). Overlapping sections were correlated to each other based on stratigraphy and loss–on–ignition 550 °C. At the A core site, a core that preserved the sediment–water interface was collected and sliced in the field at 0.25 cm intervals.

3.2. Age control

Geochronology was established using radiocarbon dating on identifiable terrestrial macrofossils, preferably charcoal (Table 1). Samples were pretreated using a standard acid, base, acid procedure (Olsson, 1986) and processed and analyzed at Woods Hole Oceanographic Institute National Ocean Sciences Accelerator Mass Spectrometry facility. The resulting ages were calibrated using CALIB 8.6 and the INTCAL20 calibration curve (Reimer et al., 2020) or CALIBomb (Reimer and Reimer, 2023). ^{210}Pb and ^{214}Pb activities were measured by direct gamma (γ) counting in a broad energy germanium detector at the University of Florida Land Use and Environmental Change Institute. These activities were used to calculate ages using the Constant Rate of Supply (CRS) method, which accounts for variability in sediment flux, according to the methodology of (Binford, 1990). Radiocarbon and ^{210}Pb ages were used in the BACON code (Blaauw and Christen, 2011) in the statistical software package "R" (R Core Development Team, 2008) to create an age depth model for each core (Fig. 3).

3.3. Geochemistry and sedimentology

Sediment cores were split lengthwise and immediately described for stratigraphy, structure, grain size, and Munsell color. Density and loss–on–ignition (LOI) were measured at 2–cm intervals using 1 cm^3

Table 1
AMS radiocarbon dates where *denotes date excluded from age model.

WHOI Number	Composite Core Sediment Depth (cm)	Material	^{14}C age (yr or BP)	Fraction modern	Error ±	Median Probability Calibrated Age (yr BP)	2σ Calibrated Age Range (yr BP)
Buck Pond							
A cores							
179,822	37.5	terrestrial plants	170		15	188	0 to 284
175,676	44.5	bark	200		20	181	0 to 294
154,744	49.0	terrestrial plants	370		15	454	330 to 498
175,677	61.0	bark	365		15	441	326 to 492
154,745	89.0	terrestrial plants	1020		20	940	921 to 963
179,818	98.5	terrestrial plants	2610		20	2746	2728 to 2756
179,819	106.5	terrestrial plants	3250		20	3459	3396 to 3548
179,820	116.5	charcoal	3430		20	3673	3585 to 3821
179,817	119.25	terrestrial plants	3460		25	3729	3640 to 3829
181,382	135.5	terrestrial plants	4980		20	5692	5604 to 5841
154,746	144.0	wood	4710		25	5404	5324 to 5578
*177344	160.0	wood	4080		30	4572	4443 to 4804
154,747	185.5	wood	5370		30	6190	6016 to 6278
C cores							
177,345	24.5	terrestrial plants		1.0863	0.0021	−51	−53 to −8
179,821	48.0	charcoal	4590		30	5314	5064 to 5448
F cores							
177,346	14.5	terrestrial plants		1.038	0.002	−62	−63 to −7
G cores							
177,347	32.5	leaf		1.1078	0.0021	−17	−49 to −2
H cores							
179,823	38.0	terrestrial plants	270		20	309	156 to 426
179,824	48.0	terrestrial plants	345		15	379	317 to 472
179,825	76.5	terrestrial plants	1560		15	1458	1385 to 1516
177,348	128.5	terrestrial plants	4440		30	5045	4879 to 5280
179,826	159.5	terrestrial plants	6410		35	7338	7266 to 7422
Halls Pond							
175,675	38.0	peat	605		15	606	552 to 645
183,723	51.25	peat	1130		15	1016	972 to 1065
179,827	59.25	peat	1400		15	1304	1290 to 1344
*177343	75.5	peat	505		15	527	513 to 541
201,177 (UCI)	101.25	peat	2265		15	2317	2184 to 2342
*179828	112.75	peat	1780		15	1654	1620 to 1714
Pigeon Marsh							
A cores							
179,829	4.75	charcoal	100		20	115	32 to 257
*177350	22.5	stick		1.3299	0.0035	−28.31	−29 to −12
179,834	23.5	charcoal	1690		20	1574	1535 to 1689
185,689	24.75	charcoal	1540		15	1400	1361 to 1511
*177349	25.0	terrestrial plants		1.0621	0.0024	−56	−58 to −8
183,722	36.25	charcoal	3920		20	4359	4290 to 4419
179,830	42.5	charcoal	3930		20	4365	4254 to 4423
*186321	60.75	wood	805		20	707	681 to 731
*184606	64.5	wood	950		15	846	793 to 917
B cores							
179,831	23.5	charcoal	7340		25	8102	8034 to 8187
177,352	47.0	charcoal	6600		35	7491	7428 to 7567
179,832	47.5	charcoal	7000		25	7838	7750 to 7930
179,833	52.0	charcoal	9980		35	11,431	11,266 to 11,686

samples. Samples were dried at 60 °C for 48 h to remove water and weighed for dry bulk density. Weight percent organic matter and carbonate content were determined by LOI at 550 °C and 1000 °C, respectively (Dean, 1974).

The composite core sequences were sampled at 1– to 2–cm intervals for Buck and Halls Pond and 0.5–cm intervals for Pigeon Marsh for weight percent nitrogen, weight percent organic carbon, C/N ratio, δ^{13}C, and δ^{15}N. LOI 1000 °C indicated no carbonate material in any sediment, so samples were lyophilized and homogenized without acidification. Samples were analyzed at the University of Arizona using a

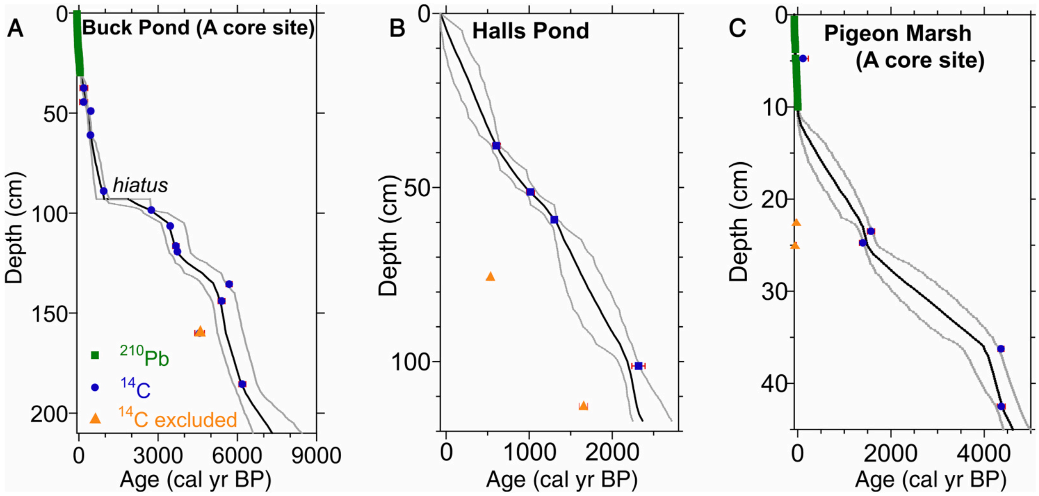

Fig. 3. BACON age-depth models for A) Buck Pond (A core site), B) Halls Pond, C) Pigeon Marsh (A core site) based on the ^{210}Pb CRS model and radiocarbon ages (Blaauw and Christen, 2011).

continuous–flow gas–ratio mass spectrometer (Finnigan Delta Plus XL) coupled to an elemental analyzer (Costech). Organic carbon isotopes are expressed in conventional delta (δ) notation as the per mil (‰) deviation from the Vienna Peedee Belemnite standard (VPDB), whereas nitrogen isotopes are reported relative to atmospheric N_2.

At two shallow water sites in Buck Pond, cores were sampled at 3– to 10–cm intervals (depending on sedimentary structures) for grain size. To remove organic matter, samples were soaked in 35% H_2O_2 for 24 h at room temperature, drained, and soaked again at 65 °C until finished reacting. To remove silica, samples were soaked in 1 M NaOH at 65 °C for 6 h and then rinsed to neutral pH. Samples were analyzed at Louisiana State University using a Malvern Mastersizer Hydro 3000E laser diffraction particle–size analyzer, which yields the distribution of grain sizes <2 mm based on laser scattering properties.

4. Results

4.1. Lithostratigraphy

The detailed stratigraphic columns for the Buck Pond transect cores show three facies: humified gyttja, lacustrine silt, and yellow sand (Fig. 4). At the deeper water site that is the focus of detailed analysis in

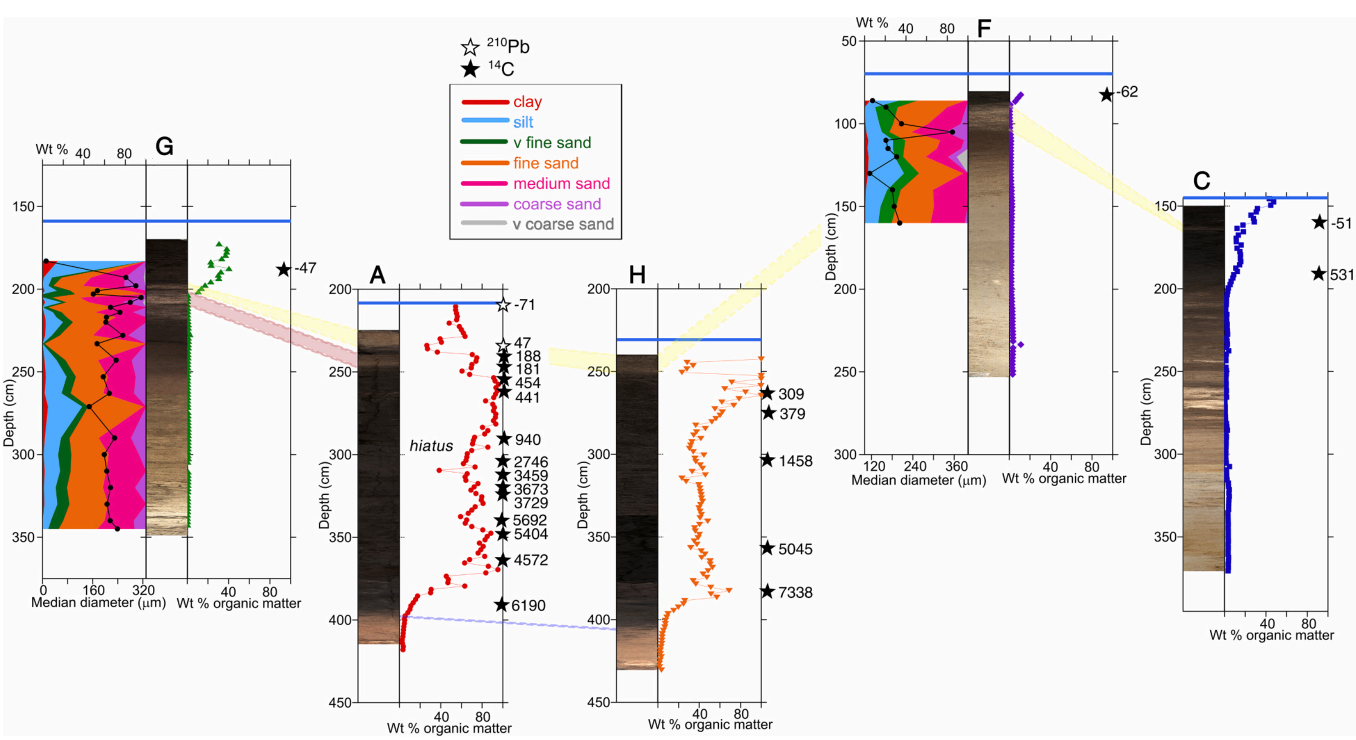

Fig. 4. Buck Pond transect core results from left to right moving along X–X' (Fig. 1C) with relative position indicating water depth (also denoted by blue line). Stratigraphic columns and weight percent organic matter are displayed for every core site where depth equals sediment and water depth. For G and F core sites, grain size distributions in weight percent are displayed in colors and median grain size diameter (μm) is displayed in black circles. Calibrated radiocarbon ages from each core site are denoted by black stars and at the A core site, top and bottom ^{210}Pb profile ages are denoted by white stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

this study (A), yellow sand at the base transitions to lacustrine silt, followed by humified gyttja for ~1 m. This terminates abruptly at 58 cm sediment depth (2.68 m water and sediment depth) with a thin 1 cm sand layer. Thereafter, there are two additional sand layers that alternate with silt from 36 to 42 cm and 20–30 cm sediment depth (2.46–2.52 m and 2.40–2.30 m water and sediment depth, respectively). At site G, the median grain size varies between 315 and 150 μm (medium to fine sand) with one data point at the top at 12 μm (fine silt). At site F, median grain size similarly varies between 355 and 115 μm (medium to very fine sand). Based on radiocarbon dates and stratigraphic units of transect cores, we estimated the lake level of Buck Pond over the last 7000 cal yr B.P. Coarse sediments (larger than silt) with low organic matter content (~ < 40%) were interpreted as littoral facies while fine-grained sediments with higher organic content were interpreted as lacustrine facies. Since high-energy shoreline environments prohibit the accumulation of fine-grained sediments, the highest elevation occurrence of lacustrine facies was interpreted as the limit of the wave base (Abbott et al., 2000; Shuman et al., 2009).

At Pigeon Marsh, there are three facies of unhumified gyttja, silt, and clay (Fig. 5). At site A, lacustrine silt dominates except for a unit of gyttja from 28 to 14 cm sediment depth (58–44 cm water and sediment depth). At site B, the basal section of the core is composed of dense clay, interrupted by several uneven changes in sediment color. Above this, around 28 cm sediment depth (118 cm water and sediment depth), silty–clay sediments appear mixed and re–worked. The upper 15 cm is comprised of gyttja. At Halls Pond, the basal 20 cm of core is lacustrine silt followed by an abrupt transition to the primary facies of unhumified gyttja (Fig. 6).

4.2. Geochronology

Twenty–two radiocarbon dates were measured on Buck Pond transect cores (Fig. 4, Table 1), thirteen of those on the deeper water core site (A) where ^{210}Pb and ^{214}Pb activities were also measured. The base of the 2.10 m of sediment from site A dates to 7300 cal yr B.P. with one hiatus inferred at 93 cm sediment depth (Fig. 3A). There is no visible change in stratigraphy at this depth; however, two radiocarbon dates 10 cm apart are 1800 years apart, inferring a pause or dramatic slowing in sedimentation and/or subaerial exposure and erosion. One date at 160 cm is anomalously young in comparison to the dates above and below it and was most likely contaminated by modern carbon during sampling and pre–treatment.

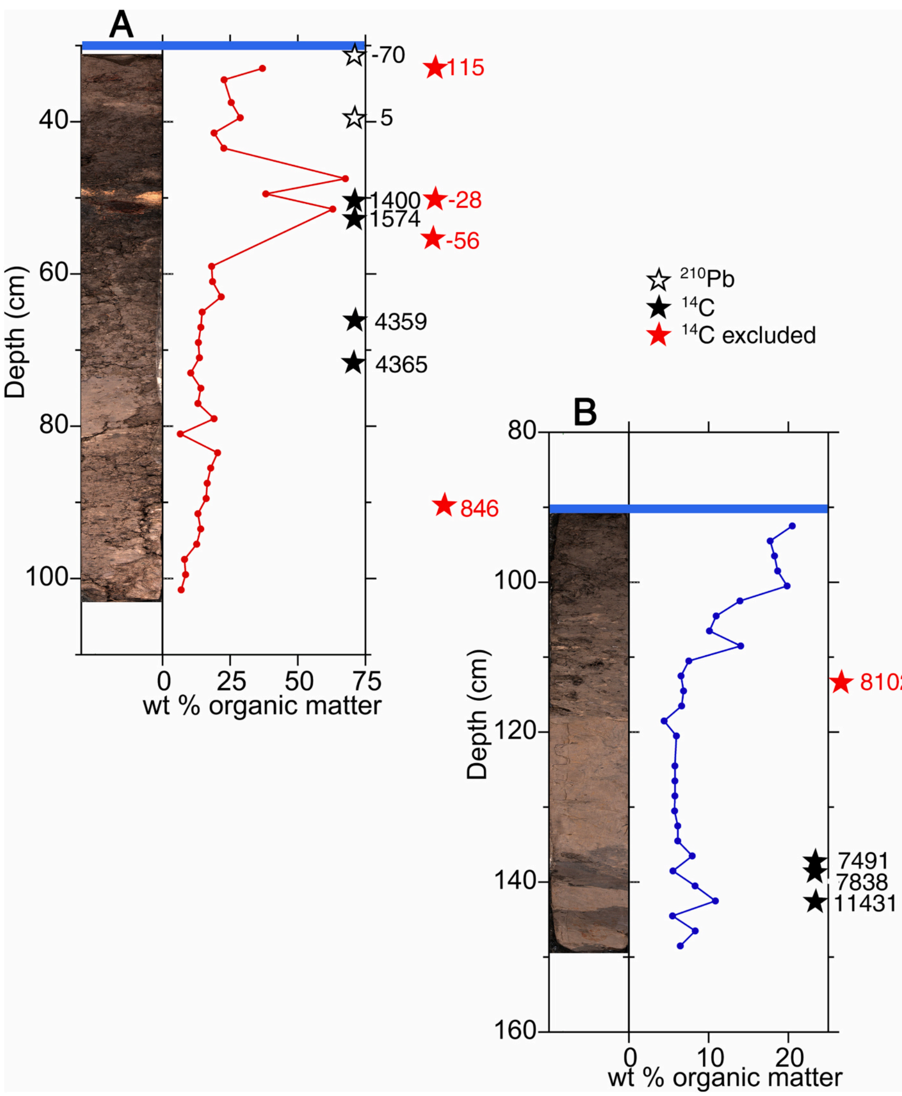

Fig. 5. Pigeon Marsh transect cores with relative position indicating water depth. Stratigraphic columns and weight percent organic matter are displayed for every core site where depth equals sediment and water depth. Calibrated radiocarbon ages from each core site are denoted by black stars (excluded dates are in red) and at the A core site, top and bottom ^{210}Pb profile ages are denoted by white stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

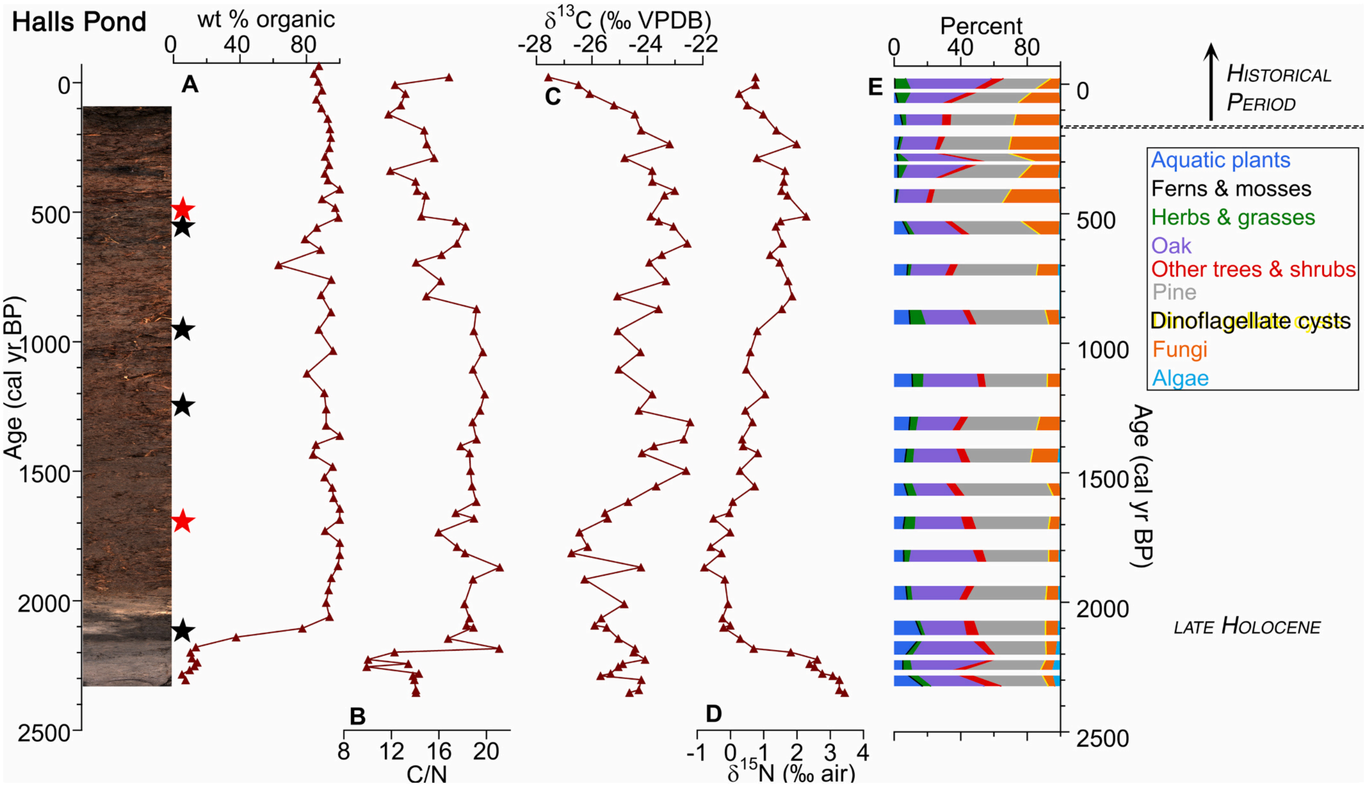

Fig. 6. For Halls Pond: A) weight percent organic matter; B) carbon to nitrogen ratio; C) organic carbon isotopes; D) nitrogen isotopes; E) palynological anlaysis (Smith et al., 2023).

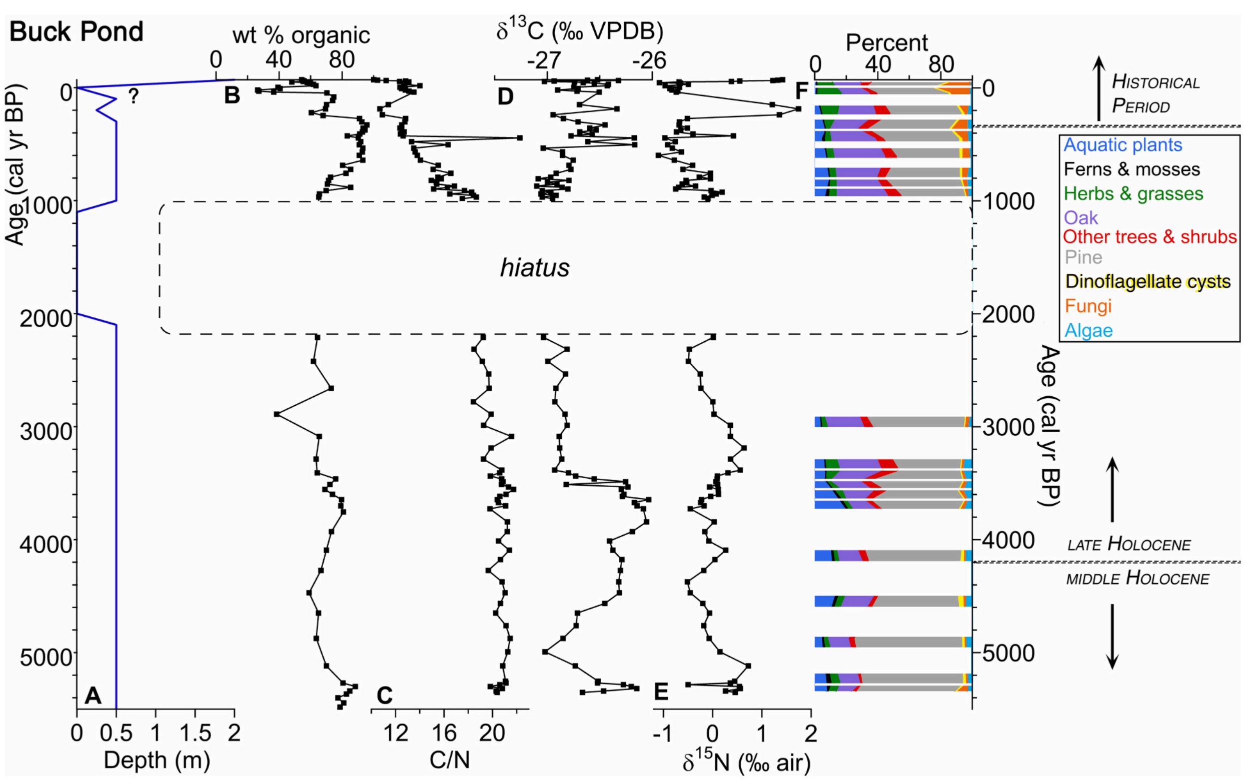

Fig. 7. For Buck Pond: A) lake level curve constructed from transect cores (Fig. 4) (see section 4.1 for methodology); B) weight percent organic matter; C) carbon to nitrogen ratio; D) organic carbon isotopes; E) nitrogen isotopes; F) palynological anlaysis (Smith et al., 2023).

Six radiocarbon dates were measured at Halls Pond (Table 1) with two dates at 75.5 and 112.75 being anomalously young, likely contaminated by modern carbon, and therefore excluded from age model construction. The nearly 1.2 m of core dates to 2400 cal yr B.P. (Fig. 3B). Due to field work circumstances, the water–sediment interface did not remain suitable for the measurement of ^{210}Pb and ^{214}Pb activities. We acknowledge that this creates uncertainty in age constraints at the top of the core and refrain from making definitive conclusions regarding the age of sediments <30 cm depth at Halls Pond.

At Pigeon Marsh, radiocarbon dates at site A derived from non–charcoal terrestrial material dated to a modern age (Table 1). As the name implies, Pigeon Marsh is today a shallow water marsh with a significant number of trees growing in the middle. This terrestrial material is most likely debris from these trees that either grew downward into the sediment and/or were dragged down during the coring and splitting processes. The radiocarbon dates on material comprised solely of charcoal did not date to a modern age and therefore were used exclusively to construct the age–depth model (Fig. 3C). At site B, radiocarbon dates on either side of some of the uneven color transitions indicate that these are most likely disconformities (Fig. 5). Additionally, the sediments that appear reworked in the upper part of the column date anomalously old, which suggests that reworking did occur. For these reasons, although site B was in deeper water, we chose not to focus on these cores for further detailed analysis and instead use them solely for their stratigraphic information.

4.3. Geochemistry

To test our primary hypotheses, we focused geochemical sampling on the last 5000 cal yr B.P. only. At Buck Pond, C/N ratios from 5300 to 2100 cal yr B.P. are stable between 18 and 21, indicating a mostly terrestrial source of organic matter (Fig. 7). After the hiatus, ratios gradually decline from 18 to 10, indicating a mostly aquatic source of organic matter, with one peak at 500 cal yr B.P. and one trough at 190 cal yr B.P., coincident with the deposition of two upper sand layers (Fig. 4). Organic carbon isotopes throughout the entirety of the record show a small range between −27‰ and − 26‰. Values are highest at the base of the core with small decreases from 5100 to 4700 cal yr B.P. and at 3500 cal yr B.P. and a small increase from 4700 to 3500 cal yr B.P. Values are stable until 500 cal yr B.P. when they increase and then exhibit high relative variability. Nitrogen isotopes are stable through most of the core, ranging from −0.5‰ to 1‰. At 430 and 190 cal yr B.P., values abruptly increase to 0.5‰ and 1.8‰, respectively, roughly coincident with the deposition of the two upper sand layers. In the most recent decade, values increase to 1.4‰.

At Halls Pond, organic matter is high and typically >80% of the total sample weight except for the lowest 20 cm (2400 to 2100 cal yr B.P.) which correspond to the lacustrine silt facies where organic matter rapidly declines to around 10% (Fig. 6). In this basal unit, C/N ratios are lower relative to the rest of the core, suggesting a dominance of aquatic organic matter, and nitrogen isotopes are >2‰, higher relative to the rest of the core. After 2100 cal yr B.P., C/N ratios increase and remain stable from 16 to 20, indicating a mostly terrestrial source of organic matter until 800 cal yr B.P. Thereafter, they decline slightly to between 16 and 12, indicating a mix of terrestrial and aquatic. Carbon isotopes from 2400 to 1800 cal yr B.P. slightly decrease from −24‰ to −26‰ and then increase to −22‰ by 1300 cal yr B.P. Values are variable and exhibit no clear trend until ~200 cal yr B.P. when there is a gradual

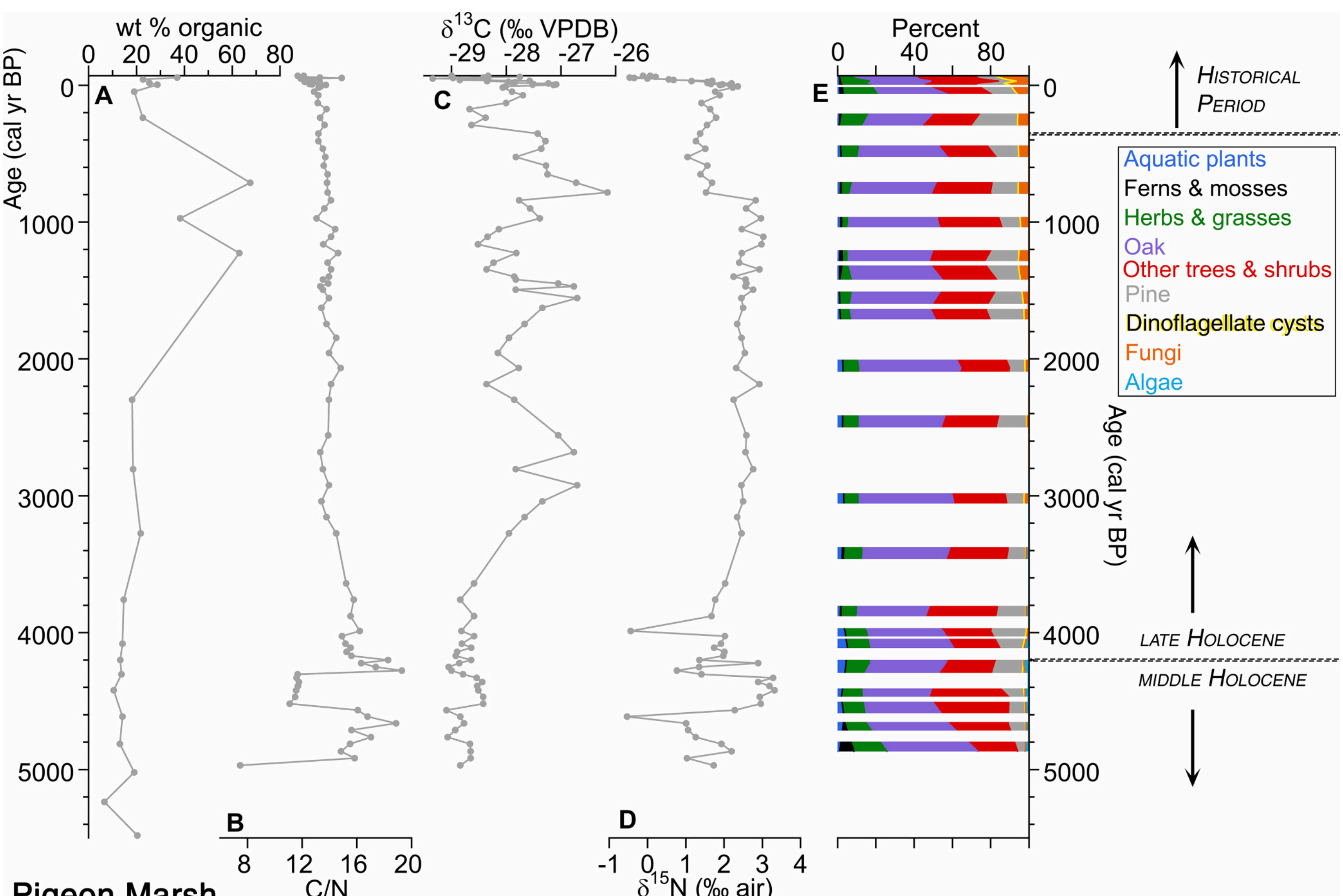

Fig. 8. For Pigeon Marsh: A) weight percent organic matter; B) carbon to nitrogen ratio; C) organic carbon isotopes; D) nitrogen isotopes; E) palynological anlaysis (Smith et al., 2023).

decrease to −28‰. From 2100 to ~200 cal yr B.P., nitrogen isotopes exhibit a slow increasing trend from 0‰ to 2‰. After 200 cal yr B.P. there is a slight decrease to 0.5‰.

At the base of Pigeon Marsh, C/N ratios and organic nitrogen isotopes have high variability with high ratios and low δ^{15}N values from 4900 to 4500 and 4300 to 4200 cal yr B.P. (Fig. 8). This is interrupted by lower C/N ratios and more positive δ^{15}N values. Thereafter, C/N ratios are stable and vary between 15 and 13. In the uppermost 2 cm, ratios decline to 11. Organic carbon isotopes are stable from 5000 to 3800 cal yr B.P., ranging between −29‰ and − 28‰, and then exhibit an increase to −26.5‰ followed by a decrease to −29‰. From 2200 to 100 cal yr B.P., organic carbon isotopes are generally positively correlated with percent organic matter, ranging between −26‰ and − 29‰. The most recent 70 years exhibit a rapid decline to −29‰. After 4200 cal yr B.P., nitrogen isotope values are stable, ranging between 2‰ and 3‰. From 800 to 0 cal yr B.P., values are similarly stable, between 1‰ and 2‰. In the last 70 years, there is a small increase to 2.2‰ followed by a rapid decrease to −0.5‰.

5. Discussion

The sediment core results are discussed in three sections: middle Holocene (~7000 to 4200 cal yr B.P.), late Holocene (4200 to 175 cal yr B.P.), and historical period (most recent ~250 years). We delineate the middle and late Holocene at 4200 cal yr B.P. based on the International Commission on Stratigraphy definition (Walker et al., 2018).

5.1. Middle Holocene (~7000 to 4200 cal yr B.P)

We interpret the sand in the basal sections of Buck Pond as the formation of the lake around 7000 cal yr B.P. as indicated by the radiocarbon dates at sites A and H (Fig. 4). There are several hydroclimate changes throughout the SE US that take place slightly earlier around 8000 cal yr B.P., but most of these suggest a period of decreased precipitation. Less negative oxygen isotope values at War Eagle Cave, AL indicate that from approximately 8000 to 6000 cal yr B.P. there was a switch from summer to winter dominated precipitation and thus drier conditions (Medina-Elizalde et al., 2022). Slightly further away, palynological studies from Jones and Singletary Lakes, NC and White Pond, SC, found that increases in annual precipitation occurred earlier in the Holocene and that by 8000 or 7000 cal yr B.P., precipitation had declined to close to modern levels (Krause et al., 2019; Spencer et al., 2017). These trends in hydroclimate are counter to what we might infer about the formation of a lake, however lake formation is not necessarily solely dependent on increases in precipitation–evaporation (P–E) balance. Much of southern Alabama is underlain by karst geology which results in limestone dissolution and collapse, creating depressions suitable for year–round water retention (Horton et al., 2017). Dissolution, collapse, and lake formation may therefore be idiosyncratic and unrelated to hydroclimate.

Following the formation and infilling of Buck Pond, the homogenous stratigraphy at sites A and H both suggest low but stable lake levels (Fig. 4). There is one radiocarbon age from site C that dates to 5300 cal yr B.P. (Table 1), however it is unclear how reliable this age is. Site C is a shallow water site which historically has occasionally dropped to very shallow levels (**Fig. S1**); it is therefore uncertain how continuously this location has remained underwater. Additionally, because site C is physically separated from the larger section of the lake by a small ridge, it may have been inundated and desiccated without concomitant changes being recorded at sites A and H. Regardless, the stratigraphy and radiocarbon ages from sites A and H strongly suggest a stable climate following lake formation, an interpretation that is supported by the palynology from site A, which shows little variation and implies stable temperature and precipitation regimes (Fig. 7F) (Smith et al., 2023). However, despite a stable climate, lake levels were not high and did not approach modern–day levels. As discussed further in section 4.3, we favor the interpretation that modern–day lake levels are due to anthropogenic manipulation rather than a particularly wet P–E balance; consequently, this implies that the period from ~7000 to 4200 cal yr B.P. was likely not particularly dry in comparison to natural "baseline" conditions.

Our results at Pigeon Marsh indicate that a substantial amount of time is missing from the stratigraphic column of site B due to periods of non–deposition and/or erosion (Fig. 5). We attribute this to episodic periods of desiccation or an extremely shallow water column. The reworked section above the disconformities is further support for this conclusion. Interestingly, site A does not show evidence for such intermittent sedimentation, which may be due to several factors. Today, the marsh is extremely shallow but, in the past, it may have been deeper, resulting in sediment focusing and infilling. Accordingly, certain areas may have been exposed while others were underwater. The assumption of uninterrupted sedimentation at site A implies extremely slow sedimentation rates. Indeed, this was inferred in the previous study of Pigeon Marsh by Watts (1971), who posited that either the entirety of the Holocene was encompassed in 80 cm of sediment or that there were hiatuses in sedimentation. Our findings support these interpretations but cannot exclude either possibility based on our radiocarbon dating density because the primary focus of our current study was from 5000 cal yr B.P. to present.

The period from 4500 to 4300 cal yr B.P. at Pigeon Marsh is characterized by lower C/N ratios and more positive δ^{15}N values, which is anomalous compared to adjacent periods. This is concomitant with a small but noticeable increase in the proportion of aquatic plants and algae (Smith et al., 2023). Together, these data indicate an increase in aquatic material in the sediment, which could be driven by a number of factors, including wetter and/or warmer conditions which increased runoff and nutrient delivery and consequently aquatic productivity. Alternatively, or in combination, a change in lake environment, such as an increase in water depth, may have decreased the delivery of terrestrial material. While interesting to investigate in future work, this increase in aquatic material is not a sustained reversal of lake environmental conditions over the intervals of interest in this study. We conclude that most of the data from site A, when considered in conjunction with the discontinuous sedimentation at site B, suggest that for much of the Holocene, Pigeon Marsh was shallow.

Taken together, the results from Buck Pond and Pigeon Marsh may indicate a somewhat lower P–E balance in both the northern and southern SE US regions in the middle Holocene as compared to the late Holocene. However, we acknowledge that many of our results do not unambiguously reflect hydroclimate variability. Therefore, we might also cautiously attribute some of the observed changes as reflecting lake basin or environment idiosyncrasies.

5.2. Late Holocene (4200 to 175 cal yr B.P)

The stratigraphy of Buck Pond deep water sites in the first part of the late Holocene is unremarkable and homogenous (Fig. 4). However, there is no evidence for lacustrine sedimentation at shallow water sites, suggesting that lake level was no >0.5 m deep (Fig. 7A). C/N ratios and δ^{13}C and δ^{15}N values are mostly invariable through this period. A constant C/N ratio around 20 indicates that terrestrial organic matter was dominant over aquatic, implying a swamp–like environment in the context of transect core interpretations. The only apparent change at Buck is the small drop in δ^{13}C values at 3500 cal yr B.P. which may indicate minor changes in primary productivity. Similarly, the stratigraphy, geochemistry, and palynology of Pigeon Marsh site A in the late Holocene exhibits no pronounced change (Fig. 8). The exception to this is δ^{13}C values which exhibit more variability. Lack of accompanying change in C/N ratios suggests that these values are not being driven by changes in organic matter source and instead reflect changes in internal carbon cycling of the lake (e.g., productivity, respiration, CO_2 exchange).

Given the modern–day expression of the phase of the PNA on precipitation amounts (Fig. 2A), we hypothesized that a switch from negative to positive conditions at 4000 cal yr B.P. (Liu et al., 2014) would result in a wetter climate at Buck Pond and a drier climate at Pigeon Marsh. This hypothesis is not supported by our results. However, there is some evidence for arid conditions beginning at 2100 cal yr B.P. at both Buck and Halls Pond. Site A at Buck indicates a period of missing time between 2100 and 1000 cal yr B.P., either through extremely reduced sedimentation, non–deposition, and/or subsequent erosional removal of sediment (Fig. 4). Site H has a radiocarbon age (1500 cal yr B.P.) that dates to the interval that is missing from A. Therefore, it is likely that lake level was extremely shallow and no more than ~0.25 m deep (Fig. 7A). Similarly, Halls exhibits several changes at 2100 cal yr B.P. that indicate an environmental change: sediment abruptly changes from silt to gyttja, percent organic matter and C/N ratios rapidly increase, and there is a decline in the proportion of aquatic plant and algal palynomorphs (Fig. 6). Together these changes suggest a shift from lacustrine deposition to a considerably shallower swamp–like environment.

We suggest that the similarly dry periods at Buck and Halls Ponds may be due to a regional climate change, particularly in the context of nearby paleorecords. War Eagle Cave, AL has a cessation of stalagmite growth from 4300 to 2600 cal yr B.P. followed by oxygen isotope values that indicate a dominance of winter precipitation and consequently drier conditions from 2500 to 1500 cal yr B.P. (Medina-Elizalde et al., 2022). Similarly, DeSoto Cave, AL has a cessation of stalagmite growth implying arid conditions from 2100 to 1700 cal yr B.P. (Aharon and Dhungana, 2017). The NAO switched from a negative to positive mean–state around 2000 cal yr B.P. (Faust et al., 2016; Olsen et al., 2012) which would have resulted in drier conditions at our study sites. Given modern–day expressions of synoptic–scale climate patterns, we hypothesized that an NAO+ state would also have resulted in drier conditions at Pigeon Marsh (Fig. 2C), but there is only limited evidence for this. Pigeon Marsh sediments abruptly shift from silt to gyttja from approximately 2700 to 300 cal yr B.P., which is accompanied by an increased amount of organic matter and generally higher $\delta^{13}C$ values (Fig. 8). However, notably there is no change in palynology nor C/N ratios, which continue to indicate a mix of aquatic and terrestrial organic matter. None of these results definitively point to lower lake levels at Pigeon Marsh. Pigeon Marsh is only 75 km east of DeSoto Cave, which does suggest dry conditions, but it is possible that the higher elevation of Pigeon Marsh keeps it cooler and wetter (170 m versus 540 m asl for DeSoto and Pigeon Marsh, respectively). We therefore conclude that there is possible, but not definitive, evidence for the importance of the NAO on SE US hydroclimate in the late Holocene. Additional records and/or proxies are an avenue for future research to further test this hypothesis.

After sedimentation resumed at site A in Buck Pond around 1000 cal yr B.P., C/N ratios display a noticeable decline towards a more lacustrine source of organic matter and an increase in weight percent organic matter (Fig. 7). In the context of continuous deposition of gyttja at both sites A and H, we suggest that the period after 1000 cal yr B.P. indicates somewhat deeper water conditions, although not deep enough to inundate site G (Fig. 4). This may reflect local and/or lake specific conditions at Buck since Halls does not show strong evidence for wetter conditions. At Pigeon Marsh, there is an abrupt drop in nitrogen isotopes at 800 cal yr B.P. that is most likely attributable to a shift in algal communities, particularly a shift towards cyanobacteria which fix atmospheric nitrogen ($\delta^{15}N$ values ~0‰) (Talbot, 2001). However, this is not necessarily indicative of deeper water conditions.

Lastly, at an estimated age of 500 cal yr B.P., there is a sand layer deposited at site A at Buck. Since this layer is thin, discrete, not deposited at site H, not accompanied by palynological assemblage change (Fig. 7F) and is accompanied by an increase in C/N ratio (Fig. 7C), we interpret this as an event deposit arising from in wash of terrestrial material (e.g., flood, hurricane). The results of the late Holocene at our three study sites do demonstrate some degree of environmental change, but it is not consistent with our hypothesis regarding the influence of the PNA and plausibly supports the importance of the NAO. We surmise that our results are either recording local environmental/lake specific conditions and/or that synoptic–scale climate patterns that influence P–E balance in the SE US at this time were more complex than can be discerned with the current density of sites. The absence of pronounced hydroclimate change in the late Holocene is generally supported by Jones and Singletary Lakes, NC where the hydrogen isotope values of leaf waxes remained relatively constant (Lane et al., 2018).

5.3. Historical period (most recent ~250 years)

The historical period is marked by profound change in lake level and environment at all three study sites. However, we attribute these changes to human activities rather than natural hydroclimate variability given their unprecedented magnitude and rate. Beginning at 230 cal yr B.P. at Buck, there is an increased proportion of herbs and grasses reflecting a more open landscape (Smith et al., 2023). This change in vegetative cover is contemporaneous with European settlement, and subsequent deforestation, in Alabama around the 1700s (Gomillion and Norrell, 2023). There is a sand layer deposited at 190 cal yr B.P. at site A, likely contemporaneous with the layer at site G marked by a pronounced increase in median grain size (Fig. 4). Larger sized particles require more energy to transport and deposit, suggesting that higher energy conditions, and therefore lower lake levels, prevailed closer to the shoreline. However, because this sand layer is not present at site H, lake level decline could not have been more than ~0.25 m and site A may have been a near–shore lacustrine environment. Alternatively, this layer may be an event deposit, although this seems unlikely because this layer is also marked by a shift to less terrestrial organic matter (lower C/N ratio) with higher $\delta^{15}N$ values. After this sand layer, there is a gradual fining upward of sediment at site A (ca 110 cal yr B.P.), although much more abrupt at site G, as evidenced by the median grain size decrease (Fig. 4). Given the rapidity with which these changes occur as well as their unprecedented occurrence in the previous 7000 years, we favor the interpretation that they are attributable to anthropogenic changes in the watershed associated with European settlement. Alteration of vegetative cover and/or agricultural conversion of land changes catchment runoff and groundwater storage, which has attendant consequences on lake level. We lack historical documentation to support this interpretation, but tree–ring records only partly support an interpretation of a natural climate driver. There were several prolonged periods of aridity from 200 to 100 cal yr B.P., but these were also punctuated by pluvial periods of similar duration but smaller magnitude (Cook et al., 2007; Stahle and Cleaveland, 1994). Perhaps a combination of anthropogenic and natural climate variability can explain the trends at Buck Pond.

At around 1900, sand is deposited at all sites in Buck with clear increases in median grain size at sites G and F, primarily driven by increases in the proportion of medium sand. At site A, there is a slight increase in C/N ratio from 11 to 13, indicating a small increase in the proportion of terrestrially sourced organic matter (Fig. 7). Given the high energy necessary to transport and deposit sand basin–wide, this could be interpreted as a pronounced drop in lake level and potentially a complete, but brief desiccation. However, it may also be the result of intense watershed erosion. One of the primary surficial geology components of the catchment is Miocene sands (Horton et al., 2017). Historical records indicate that prior to its acquisition as part of the US Forest Service in 1936, much of Conecuh National Forest was deforested (Pasquill Jr.). In the 1970s, Conecuh National Forest was plowed and scoured with industrial equipment in order to replant for slash pine (Aresco and Guyer, 1999). Within the 95% age model uncertainty of the timing of the sand layer deposition (1900 CE ± 15 years), we suggest that deforestation was the most likely driver, which resulted in the destabilization of sandy catchment soils. Subsequent scouring of the forest would only have accentuated this erosion.

At around 1970, there is rapid and consistent deposition of gyttja at all sites, delineated by increased organic matter and decreased grain sizes with higher proportions of silt (site G) or very fine sand (site F) (Fig. 4). This may suggest a several meter lake level rise, inundating all sites, establishing present–day water levels, and connecting the two sections of the basin (Fig. 7A). These most recent decades are also marked by a rapid 2.5‰ increase in $\delta^{15}N$ values. When shoreline and offshore environments become flooded, terrestrial and soil organic matter provides an abundant source of enriched nitrogen to the aquatic system (Talbot and Laerdal, 2000). A several meter rise within the historical period is unprecedented in the existence of the lake, yet there is no historical data that indicates such a drastic change in climate. It is therefore most likely that this is the result of human influence on the lake catchment. Peak timber production occurred in the mid-1980s (Pasquill Jr., 2023), which has been documented to result in increased river discharge and overland flow, increasing not only water delivery, but also particulate organic material (Campbell and Doeg, 1989). A focus on reforestation of native pine in Concecuh National Forest has only occurred in more recent years (Pasquill Jr., 2023) and the hydrologic impact may take some time to appear in the sediment record.

At Pigeon Marsh, lacustrine silt deposition returns to site A around 300 cal yr B.P. and continues until the present–day, possibly suggesting slightly higher lake levels, albeit still quite shallow. Palynology at Pigeon Marsh shows an increased proportion of herbs and grasses around 1880, indicating a more open landscape, which is likely due to land clearance associated with local agriculture (Smith et al., 2023). This generally agrees with historical records that documented extensive land clearance and settlement prior to the 1930s (Georgia Conservancy, 1998). Nitrogen isotope values exhibit the most change in the last 70 years with a rapid decline of 2.5‰ (Fig. 8). This may be due to either the influence of industrial fertilizer and/or a shift towards nitrogen fixing cyanobacteria, both with $\delta^{15}N$ values ~0‰ (Bateman and Kelly, 2007; Kendall et al., 2007). At Halls Pond, the uppermost palynology samples indicate similar increases in herbs and grasses (Smith et al., 2023).

Given the rapidity with which proxies shift at all three study sites and their coincidence with historical documentation of lake catchment changes, we interpret the last 300 to 250 years of environmental change as being driven by human activities. The magnitude of these changes, both in terms of lake hydrologic balance and biogeochemical cycling, far exceed that of middle and late Holocene changes driven by natural climate variability.

6. Conclusions

Our goal was to determine what synoptic–scale climate driver could be influencing SE US hydroclimate over the last 5000 years. Using physical, geochemical, and biological information, we inferred changes in lake hydrologic balance and environment at three lakes in the SE US. We primarily tested the hypothesis that when the PNA switched phase, the precipitation dipole that presently exists between the northern and southern SE US would switch and be discernable at our study sites. We did not find evidence to support our hypothesis but found some evidence for the importance of the NAO at 2000 cal yr B.P.; however, this was not strongly indicated nor entirely spatially coherent. While additional records are necessary to confirm this, our results may suggest that future changes in the phase and strength of the PNA and NAO will play a minimal role in exacerbating current hydroclimate extremes. Our results generally indicate fairly stable hydroclimate conditions, in agreement with other recent SE US paleo-lacustrine records. Following historical European settlement, there is an unprecedented magnitude and rate of anthropogenic impacts to the natural lake systems.

Declaration of Competing Interest

None.

Data availability

There is a link to the data repository in the acknowledgements section of the manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2023.111904.

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