ARTICLE IN PRESS

YQRES-03609; No. of pages: 9; 4C:

Quaternary Research xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Sedimentary proxy evidence of a mid-Holocene hypsithermal event in the location of a current warming hole, North Carolina, USA

Benjamin R. Tanner [a,*], Chad S. Lane [b], Elizabeth M. Martin [d], Robert Young [c], Beverly Collins [d]

[a] Department of Geosciences and Natural Resources, 331 Stillwell, Western Carolina University, Cullowhee, NC 28723, USA
[b] Department of Geography and Geology, 601 South College Road, University of North Carolina Wilmington, Wilmington, NC 28403, USA
[c] Program for the Study of Developed Shorelines, Belk 294, Western Carolina University, Cullowhee, NC 28723, USA
[d] Biology Department, Natural Science Building 132, Western Carolina University, Cullowhee, NC 28723, USA

ARTICLE INFO

Article history:
Received 28 May 2014
Available online xxxx

Keywords:
Hypsithermal
Multi-proxy
Warming hole
Biomarker
Bog
Holocene
Southeast
Climate change
Pollen
Carbon isotope

ABSTRACT

A wetland deposit from the southern Appalachian mountains of North Carolina, USA, has been radiocarbon dated and shows continuous deposition from the early Holocene to the present. Non-coastal records of Holocene paleoenvironments are rare from the southeastern USA. Increased stable carbon isotope ratios ($\delta^{13}C$) of sedimentary organic matter and pollen percentages indicate warm, dry early- to mid-Holocene conditions. This interpretation is also supported by *n*-alkane biomarker data and bulk sedimentary C/N ratios. These warm, dry conditions coincide with a mid-Holocene hypsithermal, or altithermal, documented elsewhere in North America. Our data indicate that the southeastern USA warmed concurrently with much of the rest of the continent during the mid-Holocene. If the current "warming hole" in the southeastern USA persists, during a time of greenhouse gas-induced warming elsewhere, it will be anomalous both in space and time.

Introduction

The southeastern USA is one of only a handful of locations globally that did not significantly warm over the 20th century (Alexander et al., 2013). Hypotheses offered to explain this "warming hole" include the influence of irrigation and urbanization (Misra et al., 2012), changes in sea surface temperatures (Robinson et al., 2002), land–atmosphere feedbacks (Pan et al., 2004), internal dynamics (Kunkel et al., 2006), impacts of aerosols and changes in vegetation (Portmann et al., 2009), and the link between high levels of precipitation and damped trends in daily maximum temperature (Portmann et al., 2009). High-resolution, long-term records of Holocene climate change, crucial for addressing these competing hypotheses, are lacking for the southern Appalachian region. The few records that do exist lack complete or continuous Holocene deposition (e.g. Shafer, 1988; McDonald and Leigh, 2011). Thus, as Driese et al. (2008) noted, paleoclimate modelers are forced to base interpretations on extrapolations from other, more distant, study sites within North America.

It is useful to consider the current southeastern USA warming hole in the context of previous continental-scale warm events. Extratropical temperature proxy records show evidence of warmer (than recent decades) conditions for multiple locations around the world in the early to mid-Holocene (Jansen et al., 2007). In North America, proxy records show a "Holocene thermal maximum" peak between 11–9 ka in Alaska and northwest Canada, and about 7–5 ka in northeast Canada (Kaufman et al., 2004). Other continental climate proxy records show a mid-Holocene "altithermal" between 7 and 5 ka in the southwestern and mid-continent regions of the USA (Nordt et al., 1994) and a "hypsithermal" event is present in proxy records from the northeastern USA between about 8.8 and 4.4 ka (Mullins et al., 2011).

Though there is a general lack of continuous Holocene paleoenvironmental records for the Southern Appalachians, much useful paleoenvironmental data are available for the southeastern USA. Leigh (2008) argues for a warm and wet early Holocene on the Atlantic Coastal Plain based on pollen records and reconstructions of stream channel geomorphology. The interpretation of wet early Holocene conditions is generally supported by the pollen data from the Little River site on the upper Coastal Plain of North Carolina (Goman and Leigh, 2004) and also the pollen record from Sandy Run Creek on the upper Coastal Plain of Georgia (LaMoreaux et al., 2009).

Conversely, Otvos (2004, 2006) argues for several early to mid-Holocene "hypsithermal–altithermal" intervals of increased aridity in northwestern Florida, Alabama, and southeastern Louisiana based largely on dune fields (see Goman and Leigh (2006) for an alternative view). Driese et al. (2008) also postulate multiple mid-Holocene

* Corresponding author.
E-mail address: btanner@wcu.edu (B.R. Tanner).

http://dx.doi.org/10.1016/j.yqres.2014.11.004
0033-5894/

Please cite this article as: Tanner, B.R., et al., Sedimentary proxy evidence of a mid-Holocene hypsithermal event in the location of a current warming hole, North Carolina, USA, Quaternary Research (2014), http://dx.doi.org/10.1016/j.yqres.2014.11.004

warming and drying events based on carbon isotope and multi-element data from several southeastern Tennessee floodplain soil profiles. The pollen record from Anderson Pond, TN, also suggests a mid-Holocene warming and drying trend (Delcourt, 1979). However, a later study of the Anderson Pond site suggested that the Holocene portion of the sediment record was either absent or unreliable (Liu et al., 2013). A carbon isotope and organic biomarker record from Lake Tulane in central Florida that covers the last 62,000 years does not provide evidence for mid-Holocene warming (Huang et al., 2006). In a review article, Delcourt and Delcourt (1985) suggest that mid-Holocene warming and drying extended into the mid-latitudes of the Southeast west of the Appalachians, but that warm and wet conditions existed further south and east, in the Southern Appalachian Mountains and the northern Gulf Coastal Plain. It is clear that there is a need for additional data, particularly for the region near the boundary of the inferred warm and dry early to mid-Holocene conditions vs. warm and wet early to mid-Holocene conditions. These data would also be useful for researchers interested in placing the current southeastern "warming hole" in the context of previous Holocene climate changes.

We present a multi-core and multi-proxy record of Holocene environmental change derived from organic-rich sediments from a high elevation wetland site (Panthertown Valley; Fig. 1) in the mountains of western North Carolina, USA. Collected data include bulk C and N content, bulk carbon isotope composition, *n*-alkane distributions, and pollen counts for wetland-specific and upland flora. Although there are challenges to using a multi-proxy approach (Birks and Birks, 2006), many studies have confirmed the benefits of this approach for reconstructing environmental change (e.g. Blundell and Barber, 2005; Davidson et al., 2013), particularly when combined with multi-core analysis (Lejju et al., 2005; Loisel and Garneau, 2010). This comprehensive multi-proxy record from the Panthertown core represents the first of its kind recovered from the Southern Appalachians that nearly spans the entirety of the Holocene.

Location and setting

The Panthertown Valley wetland (35°09.55′N, 83°01.30′W) has a surface area of 4.6 ha and is situated ~1115 m above sea level. The area surrounding the site was logged intermittently from the 1920's to the 1960's, partially planted with white pine shortly thereafter, and transferred to the U.S. Forest Service in 1989 (Kornegay, 2003). The wetland occupies part of a valley and is intersected by Panthertown Creek. The site is underlain by felsic mica gneiss that lies at the core of the Cashiers Antiform (Wickstrom, 1979). The wetland, which hydrologically represents a fen, is an example of the Southern Appalachian bog, typic subtype described by Schafale (2012).

Schafale and Weakley (1990) describe the typical vegetation found within Southern Appalachian bogs as "…a mosaic or zoned pattern of

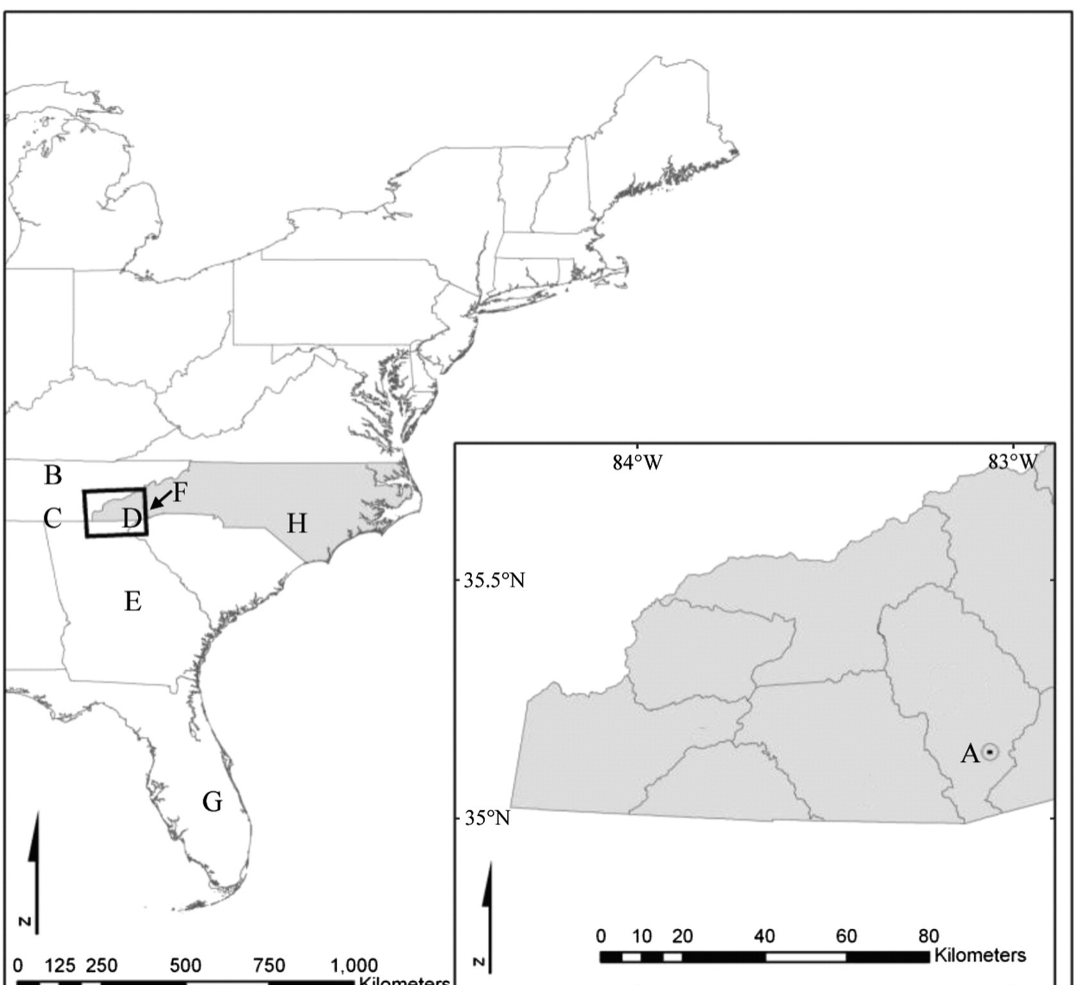

Figure 1. Map of the eastern United States showing the location of the Panthertown Valley site (Site A on inset, 35°09.55′N, 83°01.30′W) within Jackson County, NC. Other sites discussed in the text are also represented including Anderson Pond (B), Raccoon Mountain Cave (C), Horse Cove Bog (D), Sandy Run Creek (E), Flat Laurel Gap (F), Lake Tulane (G) and the Little River Site (H).

shrub thickets and herb dominated areas, much of it underlain by Sphagnum mats". There is high species diversity within the tree, shrub, and herb layers of this wetland type and the reader is referred to Schafale and Weakley (1990) for a list of typical species.

Climate data obtained for the nearby town of Highlands for the period 1877 to 2012 from the Southeast Regional Climate Center show average monthly minimum temperatures ranging from a low of −3.2°C in January to a high of 14.9°C in July. Average monthly maximum temperatures range from a low of 7.3°C in January to a high of 25.6°C in July, and average total precipitation is 209.2 cm yr^{-1}.

Methods

The Panthertown Valley wetland was probed extensively with a hand auger and the thickest deposit discovered was cored and dated (core 1). This core was collected using an Eijkelkamp Dutch auger, which is a half-spoon push core (1 m length, 3 cm diameter split core barrel) and is a type of hand coring device that does not compact sediments. Core sample recovery length was 1 m per auger drive. Core sections were cleaned (edge sediments scraped off) subsequent to recovery in order to expose fresh sediments for subsampling. These sediments were sampled from the interior of the core to avoid contamination. The core site was revisited several times between 2008 and 2012, and a series of three additional cores (cores 2–4) were collected using the same methods. A separate core (vibracore 1) was collected with a vibracoring device in order to penetrate the basal, sub-organic layer on which the Dutch auger refused. Cores 1 and 2 were collected within 10 m of each other, and cores 3, 4, and vibracore 1 were collected ~70 m distant from cores 1 and 2, but adjacent to each other.

Core 1 (165 cm total length) was subsampled at 5 cm increments, with several additional subsamples collected at obvious stratigraphic boundaries. Samples were air dried at 65 ° C, powdered, and measured for carbon (total organic carbon, or TOC) and nitrogen content using an Elementar Vario EL III Elemental Analyzer at Western Carolina University in 2008. Cores 2 (160 cm total length) and 4 (173 cm total length) were subsampled at 5 cm intervals and were measured for carbon (TOC) and nitrogen content, as well as carbon ($\delta^{13}C$) isotope composition, using a Costech Elemental Analyzer coupled to a Thermo Delta V Plus Mass Spectrometer at the University of North Carolina Wilmington in 2012. Sample treatment was the same as described for Core 1. All $\delta^{13}C$ values are presented relative to the V-PDB standard. The Panthertown wetland is a mildly acidic freshwater system where no carbonate has been observed, therefore measured bulk carbon percentages and isotope values are assumed to represent organic contributions to the sediment pool. One sample from core 4, at the 135 cm sample depth, was lost during processing/analysis.

Core 4 was separately subsampled at 10 cm intervals for pollen analysis. Samples were processed for pollen according to modified techniques of Faegri and Iverson (1989). Briefly, samples were gently broken up with a mortar and pestle and 0.5 cm^3 of material was weighed and processed for pollen. One tablet of *Lycopodium clavatum* spores was added to samples prior to processing in order to determine pollen concentrations. Samples were treated with 10% hydrochloric acid, 5% potassium hydroxide and were then sieved through a 125 μm screen. Samples were then treated with 49–52% hydrofluoric acid and an acetolysis solution. The remaining pollen residue was stained with Safranin and suspended in silicone oil where it was then counted under a binocular light microscope at 400×. Three hundred grains of arboreal pollen were counted for each slide. Percentages of *Quercus* and *Castanea*, the two most abundant arboreal taxa, are presented. Percentages of wetland specific taxa (*Alnus*, *Sphagnum*) are presented along with percentages of Poaceae. Percentages of *Quercus*, *Castanea*, and *Alnus* are calculated relative to total arboreal pollen. Percentages of *Sphagnum* and Poaceae are calculated relative to total identified pollen and spores.

Core 3 (142 cm total length) was subsampled at irregular intervals based on visual characteristics of the core and the subsamples were prepared for lipid biomarker analysis. Lipid extraction and *n*-alkane separation were performed following the methods outlined by Wang et al. (2003) and subsequently modified by Tanner et al. (2010). Dried and ground (~0.5 g) samples were extracted ultrasonically in 50 ml 9:1 (v/v) dichloromethane/methanol for 10 min. This extraction was repeated three times for each sample. The solvent was removed each time after centrifugation (3500 rpm, 10 min), and all extracts were combined. The total lipid extracts were evaporated under an N_2 stream to near dryness and then re-dissolved in 10 ml hexane. The hexane was further evaporated down to about 2 ml and the samples were transferred to glass vials for further column separation. The *n*-alkanes were separated using 1.0 × 25 cm glass chromatography columns packed with activated silica gel (100–200 mesh). On top of the silica gel, ~10 mm activated Cu was added to remove any sulfur in the extracts. After adding the extract to the columns using a glass pipette, *n*-alkanes were eluted with 25 ml of hexane. The eluate was evaporated to ~1 ml and samples were then capped and stored at −20°C until analysis.

Individual alkanes were separated and characterized using an Agilent 7890 Series GC interfaced to an Agilent 5973SC mass selective detector (MS) at Western Carolina University. Compound separation was achieved using a 30 m × 0.25 mm i.d. × 0.25 μm film thickness ZB-5 ms column (Phenomenex, CA, USA). Oven temperature was set initially at 130°C for 2 min, then ramped at 10 °C min^{-1} to 300°C and held isothermal for 23 min. The detector interface was set at 280°C. Injections were performed in split mode and ultrapure helium was employed as a carrier gas. GC/MS analyses were performed in the electron impact (EI) ionization mode with an electron energy of 70 eV and the mass range m/z 40 to 400 was scanned at 2 scans s^{-1}. Target analytes were identified within total ion chromatograms by matching their retention times and mass spectra to standard reference materials and the National Institute of Standards and Technology mass spectral library. Concentrations of individual *n*-alkane homologues were calculated based on the standard calibration curve of each corresponding authentic standard.

Distributions of organic compounds were quantified using the carbon preference index (CPI) and average chain length (ACL). We used versions of the CPI and ACL similar to those employed by Wang et al. (2003) and described by Tanner et al. (2010) that are based on the absolute abundance of *n*-alkanes with chain lengths ranging from C_{23} to C_{34} where:

$$\mathrm{CPI} = \sum \mathrm{odd}\ C_{23}\ \mathrm{to}\ C_{33} \Big/ \sum \mathrm{even}\ C_{24}\ \mathrm{to}\ C_{34}$$

The ACL is calculated as follows:

$$\mathrm{ACL} = \sum [C_i] i \Big/ \sum [C_i]$$

where i is the carbon number from C_{23} to C_{34} and $[C_i]$ is the concentration. CPI values were calculated using GC/MS reported concentrations.

Several samples from cores 1–4 were sent to Beta Analytic for radiocarbon dating (Table 1). Sample depths represent the mid-point of the sediment section sent for radiocarbon dating. Radiocarbon analysis was performed following standard procedures for organic sediments and calibrations were calculated using OxCal v. 4.2 and the INTCAL 13 calibration database (Reimer et al., 2013). Reporting of radiocarbon data follows published suggestions (Bartlein et al., 1995). Linear interpolation was used to assign ages between dated horizons. The age/depth model is based on the mid-point of the sediment section used for radiocarbon dating and the median (see Telford et al. (2004)), 2σ age in cal yr BP (present = 1950).

Please cite this article as: Tanner, B.R., et al., Sedimentary proxy evidence of a mid-Holocene hypsithermal event in the location of a current warming hole, North Carolina, USA, Quaternary Research (2014), http://dx.doi.org/10.1016/j.yqres.2014.11.004

Table 1
Radiocarbon data for the Panthertown Valley cores. Sample depths are in cm below the ground surface. Calibration procedures are described in the Methods section.

Sample depth (cm)	Conventional radiocarbon Age (^{14}C yr BP)	δ^{13}C (‰)	Calibrated 2σ range (cal yr BP)	Calibrated 2σ range Median (cal yr BP)	Dated material	Laboratory #
Core 1						
152	7150 ± 50	−25.3	8149 to 8144 8106 to 8095 8053 to 7916 7905 to 7854	7973	Peat	Beta-242155
Core 2						
25	1740 ± 40	−26.1	1777 to 1758 1739 to 1551	1651	Charred material	Beta-250456
50	4030 ± 40	−21.9	4784 to 4766 4615 to 4416	4497	Organic sediment	Beta-250457
95.5	4950 ± 70	−23.4	5892 to 5804 5796 to 5779 5773 to 5587	5693	Organic sediment	Beta-250458
142.5	5850 ± 50	−26.6	6784 to 6529 6519 to 6507	6666	Wood	Beta-250459
158.5	4840 ± 50	−26.7	5697 to 5694 5662 to 5467	5584	Charred material	Beta-250460
158.5	3910 ± 40	−26.3	4499 to 4187 4440 to 4232 4197 to 4183	4343	Peat	Beta-251927
Core 3						
71	4550 ± 40	−21.4	5434 to 5423 5320 to 5211 5196 to 5049	5165	Organic sediment	Beta-295385
136.5	6870 ± 40	−26.5	7790 to 7619	7701	Peat	Beta-295386
Core 4						
77.5	4650 ± 30	−23.2	5466 to 5345 5335 to 5312	5405	Organic sediment	Beta-317062
147.5	7250 ± 40	−26.5	8167 to 7983	8076	Charred material	Beta-317063

Results and discussion

Radiocarbon dates indicate organic deposition beginning around 8000 cal yr BP for cores 1, 3, and 4 (Table 1; Fig. 2) from Panthertown, making this one of the few wetland sedimentary records from the Southern Appalachians spanning the early to late Holocene. The basal date on charred material from core 2 (Beta-250460) was found to be out of stratigraphic order. A second date was obtained on peat (Beta-251927) from this sample depth due to this discrepancy and a similar age to the other basal date from core 2 (Beta-250460) was returned. The remainder of the radiocarbon dates from core 2 are in stratigraphic order. The inverted ages for the basal samples from core 2 (Beta-250460 and Beta-251927) may be due to loss of sediment from the bottom of the core during extraction and subsequent "suck up" of overlying sediment as the core was extracted. The stratigraphy at depth was uniform for core 2 (Fig. 3) and the break in the stratigraphy that one would expect with "suck up" would be difficult to see, especially with relatively uniform organic staining of the mineral sediments. Because of this age/depth discrepancy, the other basal data for core 2 (C, N, and isotope data) should be interpreted with caution. Vibracore 1 represents an alluvial deposit which was present below the organic deposit. This alluvium has not been dated.

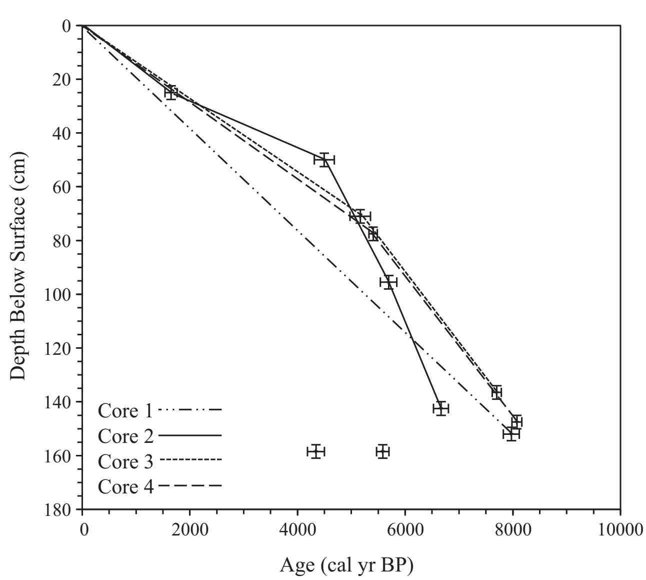

Figure 2. Age-depth model for the Panthertown site. All radiocarbon dates from cores 1–4 are plotted vs. depth. X-axis error bars (2σ) and y-axis error bars (5 cm sample thickness) are shown. Specific age/depth information with respect to individual cores is presented in Table 1. The lines on the graph show changes in the sedimentation rate and connect the data points for each core separately. These lines are forced through zero. The two radiocarbon dates that are out of stratigraphic order are shown on the graph but are not connected by a line.

The age–depth relationship, taking into account all radiocarbon dates obtained, indicates that there is continuous, or near-continuous, deposition at the site from the early Holocene to the present, although there is apparently some variability in the deposition rate (Fig. 2). There appears to be a slight decrease in the sedimentation rate near the top of the core. The equation for a best-fit line, excluding the two inverted dates for core 2, yields an overall sedimentation rate of 0.022 cm yr^{-1}.

Core 4 has been studied in the most detail because it was obtained after we acquired the ability to analyze pollen at Western Carolina University. Carbon percentages for this core are low near the bottom (near 5%) and increase steadily up-core, to >30%. There is one obvious excursion to a high value around 5250 cal yr BP (Fig. 3). The consistently high carbon content (>5%) is characteristic of wetland soil. The visual core description (Table 2) also shows indications of reduction (chroma </= 2) and anoxic conditions throughout the sediment profile. This is true for the other cores as well. Cores 1–4 all contain an upper, organic-dominant layer with a more mineral-rich, but still highly

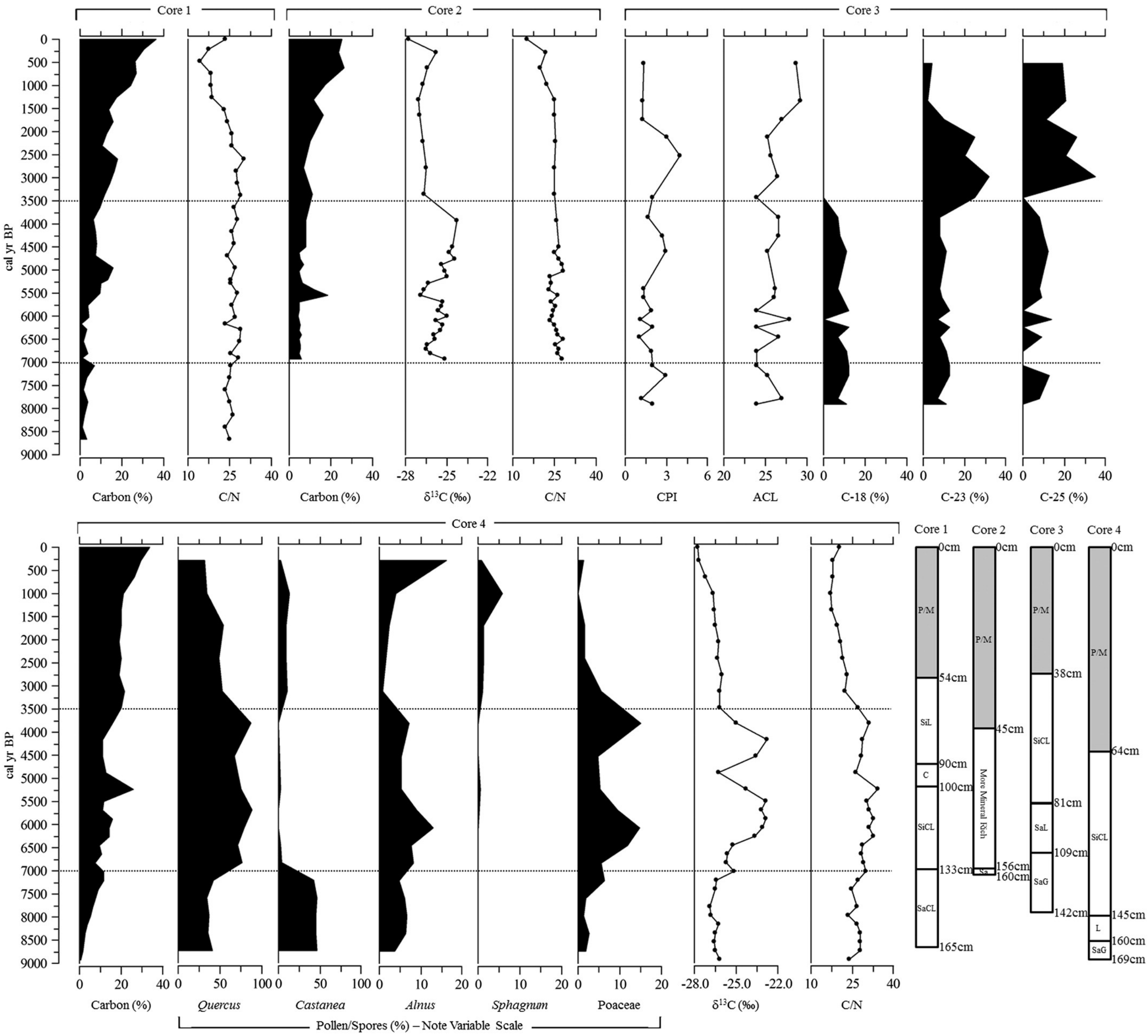

Figure 3. C/N ratios and organic carbon percentages are presented vs. calendar age for cores 1, 2, and 4. $\delta^{13}C$ values are presented vs. calendar age for cores 2 and 4. ACL and CPI values for *n*-alkane biomarkers along with relative percentages of the C_{18}, C_{23}, and C_{29} homologues are presented vs. calendar age for core 3. Percent pollen/spores of Core 4 sediments are also presented vs. calendar age. *Quercus*, *Castanea*, and *Alnus* percentages are presented relative to total arboreal pollen. *Sphagnum* and Poaceae percentages are presented relative to total identified pollen and spores. Age control (y-axis) is provided using linear interpolation between dated horizons (Table 1). The dashed line illustrates the inferred beginning and end of mid-Holocene warm/dry conditions. Core descriptions with texture are presented vs. age for cores 1–4. Depth is indicated at stratigraphic boundaries. The texture by feel method (Thein, 1979) was used for cores 1, 3, and 4. A general description was used for core 2. For the texture descriptions, P/M = Peat/Muck, Sa = Sand, Si = Silt, C = Clay, L = Loam, and G = Gravel. The mineral sediments are organic rich (~5% or greater organic carbon content throughout the profiles). Core 4 was subsampled and processed for pollen analysis. The core description for core 4 presented here was from a core that was recovered directly adjacent to core 4 that was removed specifically for the macroscopic description.

organic, underlying layer (Fig. 3). The vibracore, which was taken adjacent to cores 3 and 4, penetrated below the organic deposit and includes underlying alluvium. The base of cores 3 and 4 also contained sand and gravel, which likely represent alluvium (Fig. 3). The fact that the organic deposit rests on alluvium suggests that the wetland may have developed on a former stream channel near the location of cores 3, 4, and the vibracore. It is more difficult to interpret the paleoenvironment that precedes the wetland in the vicinity of cores 1 and 2 since these cores contain organic-rich mineral sediments at their base (similar to the remainder of the organic-rich mineral sediment in these cores) and the material that the cores refused on was not captured.

Core 4 *Alnus* pollen percentages are high at depth, decrease from 3500 to 1000 cal yr BP, and then increase again from 1000 cal yr BP to the present. The decline from 3500 to 1000 cal yr BP coincides with an increase in *Sphagnum* spores. Taken together, these data indicate a persistent wetland environment at the core location from before 8500 cal yr BP to the present. This is supported by the presence of organic-rich peat and mineral sediment throughout the collected cores (see carbon percentages in Fig. 3). Poaceae pollen percentages are elevated from ~7250 to 5500 cal yr BP and from 4500 to 3000 cal yr BP, and then decline to the surface. The increased Poaceae at depth coincides with an increase in $\delta^{13}C$, which is at a maximum value of −22.8‰ at depth, but decreases to a minimum of −28‰ near the surface.

Carbon isotope ratios of organic matter are commonly used as a climate proxy in continental settings. The abundance of plants utilizing the

Table 2
Core sediment color descriptions for Panthertown Valley. Descriptions for cores 1, 3, and 4 include Munsell colors. A general description was used for core 2. The color description for core 4 presented here was from a core that was recovered directly adjacent to core 4 that was removed specifically for the macroscopic description.

Core depth	Color	Core depth	Color
Core 1		Core 2	
0–54 cm	5YR 2.5/1	0–5 cm	Very dark brown
54–90 cm	10YR 2/1	5–42 cm	Dark brown/black
90–100 cm	10YR 2/1	42–90 cm	Light gray
100–133 cm	2.5YR 2.5/1	90–147 cm	Dark brown/black
133–165 cm	5YR 2.5/1	147–160 cm	Dark brown
Core 3		Core 4	
0–27 cm	10YR 2/2	0–19 cm	10YR 2/2
27–38 cm	10Y 2.5/1	19–63.5 cm	10YR 2/1
38–70.5 cm	10Y 2.5/1	63.5–75.5 cm	10YR 2/1
70.5–81 cm	5GY 2.5/1	75.5–145 cm	5G 2.5/1
81–109 cm	5GY 2.5/1	145–160 cm	5G 2.5/1
109–136 cm	5GY 3/1	160–169 cm	NA
136–142 cm	2.5Y 6/2		

C_3 vs. C_4 photosynthetic pathway is determined to a large extent by temperature, aridity, exposure to sunlight, and pCO_2 levels (Ehleringer et al., 1997). C_4 plants have higher water use efficiency and are relatively more abundant when conditions are warmer, drier, or when there is low pCO_2 (Ehleringer et al., 1997). The large difference in $\delta^{13}C$ values between plants that utilize the C_4 pathway vs. the C_3 pathway (around −14‰ vs. −28‰) can be used to quantify their relative contributions to the sedimentary carbon pool (O'Leary, 1988). Carbon isotopic composition also correlates with drought stress and water use efficiency for C_3 plants (Farquhar et al., 1989). More water efficient plants have more positive $\delta^{13}C$ values (O'Leary, 1988). Therefore, in a water-stressed environment (i.e. high temperature and/or drier), one should expect more positive $\delta^{13}C$ values, either because of a higher proportion of C_4 plants, or because of increased water-stress in C_3 plants. Atmospheric pCO_2 during the Holocene is relatively stable prior to the industrial revolution, varying between about 260 to 280 ppmv (Indermühle et al., 1999). Therefore, variations in $\delta^{13}C$ values of organic matter during the Holocene in locations where C_4 plants are present are likely related to warmer and/or drier conditions or drought stress in C_3 plants.

The fact that $\delta^{13}C$ values in core 4 co-vary with Poaceae percentages (Fig. 3) suggests that C_4 plants are abundant when Poaceae percentages and $\delta^{13}C$ values are high. C_4 plants make up about 37% of species in the grass flora of the Southern Appalachian Region near the Panthertown core site (Teeri and Stowe, 1976). We use a mass balance equation similar to that employed by Driese et al. (2008),:

$$\delta^{13}C = -28‰(X) \pm 14‰(1-X)$$

where X = fraction of vegetation that utilizes the C_3 photosynthetic pathway. This calculation suggests a maximum of 37% C_4 plants during the excursion to less negative $\delta^{13}C$ values at depth and a minimum of 1.5% C_4 plants near the surface. Although C_4 species are not part of the typical vegetation recorded in Southern Appalachian bogs (see Schafale and Weakley (1990)), a general vegetation survey of Panthertown Valley (Pittillo, 1994) shows that C_4 grasses, including *Andropogon virginicus*, *Panicum* spp., and *Schizachyrium scoparium*, are present around the wetland (see Waller and Lewis (1979) for a list of C_4 grasses). The fact that the higher $\delta^{13}C$ values, which likely represent organic matter deposited in situ, correspond to Poaceae increases suggests that the increase in C_4 grasses is, at least partially, taking place within the wetland itself. A Poaceae pollen increase has also been documented at nearby Horse Cove Bog, near Highlands, NC, at this time (Delcourt and Delcourt, 1997), which suggests that the mid-Holocene increase in C_4 grasses recorded at Panthertown was likely part of a regional vegetation shift. We interpret the increase in C_4 plant abundance as reflecting warmer and drier conditions at the site from ~7250 to 5500 cal yr BP and then again from ~4500 to 3000 cal yr BP. This record indicates multiple mid-Holocene warm/dry events, in agreement with Driese et al. (2008).

We also present pollen curves for *Quercus* and *Castanea*, the two most abundant arboreal taxa represented in the pollen record from Panthertown (Fig. 3). Pollen data are presented in their entirety in Martin (2014). The *Quercus* and *Castanea* pollen are likely derived from outside of the wetland from a terrestrial environment since no *Castanea* species and none of the four *Quercus* species (*Quercus coccinea*, *Quercus montana*, *Quercus rubra*, *Quercus velutina*) recorded in extant Panthertown vegetation (Pittillo, 1994) have a wetland indicator status of facultative, facultative wetland, or obligate wetland on the National Wetland Plant List for the Eastern Mountains and Piedmont Region (Lichvar et al., 2014). *Castanea* most often grows on well-drained, subxeric to mesic soils and is historically known as an upland ridgetop dominant, although it can tolerate a wide range of soils (Paillet, 2002). *Quercus* species present in Panthertown today have a similar range of moisture tolerance, and are primarily associated with xeric to mesic sites in the Southern Appalachian mountains (Weakley, 2012). It has been noted that the dominance of ambiguous pollen types such as *Pinus* spp. and *Quercus* spp. that cannot be reliably identified beyond the generic taxonomic level and contain species adapted to a wide range of environmental variables often hinder paleoclimatic interpretations for the southeastern USA (Otvos, 2005).

There is a mid-Holocene increase in the percentage of *Quercus* pollen recorded at Panthertown that coincides with a decrease in *Castanea* (Fig. 3). The timing of the *Quercus* increase/*Castanea* decrease also coincides with the hypothesized increase in C_4 grasses within the wetland at Panthertown. Thus, there is a change in the terrestrial pollen signal that parallels the change in the wetland paleoenvironmental record. Although it is difficult to derive paleoclimatic information from the terrestrial pollen curves at Panthertown, the obvious change in species dominance that occurs in the terrestrial environment along with the hypothesized increase in C_4 grasses within the wetland demonstrates a mid-Holocene environmental change both in and outside of the wetland at Panthertown. The wetland data suggest that this environmental change results from warming and drying.

Delcourt and Delcourt (1985) suggest that mid-Holocene warming and drying extended into the mid-latitudes of the Southeast USA west of the Appalachians, but that warm and wet conditions existed further south and east in the Southern Appalachian Mountains and the northern Gulf Coastal Plain. Our data suggest mid-Holocene warm and dry conditions in the Southern Appalachian Mountains in the vicinity of the Panthertown site. The data from core 4, put into the context of observations from other studies in the southeast, suggest that the dividing line between mid-Holocene warm and wet conditions vs. warm and dry conditions exists further south and east of our site.

High C/N ratios (generally above 20) are typical of organic matter originating from vascular land plants while lower C/N ratios suggest increased algal contributions (Meyers, 1994). C/N ratios for core 4 are generally above 20, indicating input from vascular plants, with a notable exception from ~300 to 1300 cal yr BP (Fig. 3). The decreased C/N ratio over that time period could indicate increased algal contributions and perhaps wetter conditions at the site during the late Holocene.

Carbon percentages for core 2, which was recovered ~70 m distant from core 4, are also low at depth and more elevated near the surface. Carbon ranges from a low of 5% near the bottom of the core to a high of 26% near the surface (Fig. 3). There is a spike in carbon content at around 5250 cal yr BP, similar to the spike in carbon seen in core 4 at 5500 cal yr BP (Fig. 3). It is tempting to view this as a synchronous event. Carbon/nitrogen ratios for core 2 are high at depth and lower near the surface. The generally high values (>20) indicate that vascular land plants are dominant. This observation is supported by data available for core 1, where a similar spike in carbon occurs ~5750 cal yr BP (Fig. 3). Likewise, C/N ratios for core 1 are high at depth and generally lower near the surface, except for the sample nearest the surface, which has a slightly higher ratio. The carbon isotope data from core 2 also show the same general trends as the $\delta^{13}C$ values from core 4 (Fig. 3), with elevated values at depth and a decline around ~3500 cal yr BP to the present. This provides further support for increased C_4 plant abundance in the mid-Holocene, which we relate to warm and dry conditions.

Core 3 was analyzed for abundances of *n*-alkane biomarkers. As summarized in Tanner et al. (2010), peak abundances of *n*-alkanes from higher plants are generally within the C_{27} to C_{33} range. Non-emergent, freshwater plants are characterized by an enrichment in C_{25}, with C_{23} also common (Ficken et al., 2000; Chikaraishi and Naraoka, 2003), while algal and cyanobacterial inputs are signaled by a higher abundance of C_{17}, or the combination of C_{15}, C_{17}, and C_{19} (Han et al., 1968; Gelphi et al., 1970; Blumer et al., 1971; Giger et al., 1980; Cranwell et al., 1987), or C_{15} to C_{32} without an odd/even preference (Weete, 1976). C_{14} to C_{20} *n*-alkanes without an odd/even preference are a biomarker for photosynthetic bacteria (Albro, 1976), while non-photosynthetic bacteria produce *n*-alkanes ranging from C_{26} to C_{30} without an odd/even preference.

Johnson and Calder (1973) found that CPI values near one indicate bacterial activity, while vascular plants have values ranging from ~3 to 40 (Collister et al., 1994; Chikaraishi and Naraoka, 2003; Wang et al., 2003). Core 3 CPI values are generally low, potentially indicating significant bacterial degradation of the sediments (Table 3, Fig. 3). Organic biomarker data must be viewed within this context. ACL values are generally lower at depth, increase to above 26 by 2000 cal yr BP, and remain elevated to the surface. ACL values are higher near the surface (>28) and decline to below 26 by 2000 cal yr BP. One sample near 6100 cal yr BP is above 27. The low ACL values before 2000 cal yr BP could be indicative of a lower abundance of higher plants at those sample depths. There is a high proportion of the C_{18} *n*-alkane from the core bottom to 3500 cal yr BP. C_{18} is absent from 3500 cal yr BP to the surface. C_{18} is a biomarker for photosynthetic bacteria (Albro, 1976) and its presence at depth is consistent with organic matter degradation and decomposition that would be found in a warmer, drier mid-Holocene environment. A lack of odd over even predominance, at lower and higher chain lengths, supports the bacterial degradation hypothesis.

Taken together, our pollen and chemical data suggest a warm, dry site during the mid, and perhaps early-Holocene, with cooler and wetter conditions after. Two other wetland sites in the region, Horse Cove Bog (Delcourt and Delcourt, 1997) and Flat Laurel Gap (Shafer, 1988) show organic sediment deposition beginning between 3900 and 3400 yr BP, consistent with the beginning of the inferred cooler, wetter conditions at Panthertown. Our inference of a warmer regional early/mid-Holocene is broadly consistent with data from other sites studied on the Atlantic Coastal Plain (e.g. Goman and Leigh, 2004; LaMoreaux et al., 2009), although our results suggest that this warming was coupled with drying. Our data suggest that the hypothesized mid-Holocene warming and drying in the mid-latitudes of the Southeast USA (Delcourt and Delcourt, 1985) extended into the Southern Appalachians as well. Our pollen and carbon isotope data indicate multiple mid-Holocene warm/dry intervals for the southern Appalachian region, which is in agreement with the findings of Driese et al. (2008). Our results also agree well with unpublished, recent work that is ongoing in the Southern Appalachian region at Raccoon Mountain Cave, where carbon and oxygen isotope records from speleothems reveal three major drought episodes between ~7400–6890 yr BP, ~5950–5340 yr BP, and ~4870–4050 yr BP (Driese et al., 2012; Li et al., 2012).

The timing of these hypothesized drought episodes generally agrees with shifts to C_4 vegetation seen in our cores between ~7250–5500 cal yr BP and from ~4500–3000 cal yr BP (Fig. 3). It should be noted that a calcite speleothem record likely has a more direct and instantaneous response to changing climatic conditions than that which can be inferred from changes in plant communities recorded in sediments. The ~5340–4870 yr BP wet phase identified in the speleothem study also agrees well with a return to a C_3 dominated plant community seen in our cores between ~5500–4500 cal yr BP. Sedimentary, pedogenic, and stable carbon isotope records from multiple floodplains along the Tennessee River also indicate a period of aridity from 8.0 to 5.0 ka that is apparently the result of an eastward intensification of the North Atlantic Subtropical High (Kocis, 2011). Our data indicate that there was a mid-Holocene hypsithermal event in the southern Appalachians, and that the regional climate was broadly synchronous with other sites that record a mid-Holocene hypsithermal in North America, and more specifically in the Southern Appalachians.

Conclusions

The Panthertown site provides the most complete record of Holocene environmental change thus far available for the Southern Appalachians. Multi-proxy data from multiple cores recovered from the site suggest warm, dry mid-Holocene conditions. This inference is

Table 3
Organic biomarker *n*-alkane concentrations along with CPI and ACL values for each sample depth. The most abundant homologue is in bold for each sample depth.

Estimated age	n-Alkane abundance (μg g^{-1})																				
(cal yr BP)	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	CPI	ACL
535	0.00	0.00	0.00	0.00	0.00	5.23	5.93	7.01	10.66	12.41	14.41	16.10	26.44	35.43	**57.72**	39.32	36.83	17.64	16.04	0.00	1.34	28.68
1330	0.00	0.00	0.00	0.00	0.00	0.00	8.63	9.76	13.46	18.28	23.78	32.32	60.37	95.15	**164.8**	121.5	118.6	57.43	35.48	10.63	1.24	29.19
1727	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.67	6.88	6.97	6.78	6.90	7.10	6.97	**7.63**	7.10	6.92	0.00	0.00	0.00	1.26	27.04
2125	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.06	12.22	12.06	0.00	0.00	0.00	**12.71**	0.00	0.00	0.00	0.00	0.00	3.01	25.30
2522	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.91	11.10	10.95	0.00	11.21	0.00	**11.57**	0.00	0.00	0.00	0.00	0.00	4.02	25.64
2975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.86	0.00	0.00	0.00	2.94	0.00	**3.06**	0.00	0.00	0.00	0.00	0.00	NA	26.40
3428	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.77	1.78	**1.81**	1.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.96	24.00
3862	0.00	2.29	0.00	2.38	0.00	2.43	2.42	2.52	2.60	2.68	2.66	2.56	2.58	2.58	**2.77**	0.00	2.52	0.00	0.00	0.00	1.68	26.61
4259	3.32	3.43	0.00	3.54	0.00	0.00	3.60	3.69	3.83	3.80	3.78	3.79	3.90	0.00	**4.72**	0.00	4.42	0.00	0.00	0.00	2.72	26.61
4598	2.07	2.14	0.00	2.20	0.00	0.00	2.22	2.27	2.32	2.36	2.28	0.00	0.00	0.00	**2.38**	0.00	0.00	0.00	0.00	0.00	2.96	25.27
5396	2.58	2.56	2.41	2.58	0.00	2.58	2.54	2.69	3.01	**3.13**	3.11	2.63	2.76	0.00	2.91	2.76	0.00	0.00	0.00	0.00	1.38	26.20
5605	3.07	3.18	0.00	3.26	0.00	0.00	0.00	3.39	3.41	3.42	3.46	3.48	3.47	3.47	**3.51**	0.00	0.00	0.00	0.00	0.00	1.34	26.02
5872	1.84	1.91	0.00	1.96	0.00	1.98	0.00	2.00	2.03	**2.07**	2.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.95	24.00
6081	0.00	0.00	0.00	0.00	0.00	0.00	1.63	2.06	3.23	3.83	3.61	3.55	4.35	5.00	**6.52**	5.44	3.66	2.58	2.22	0.00	1.16	27.91
6232	**1.84**	1.68	0.00	1.60	0.00	1.64	0.00	1.68	1.70	1.70	1.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.97	23.99
6441	1.90	1.85	0.00	1.82	0.00	1.84	0.00	1.86	1.96	1.88	1.95	1.91	1.98	2.02	**2.27**	1.94	0.00	0.00	0.00	0.00	1.05	26.56
6754	1.95	2.02	0.00	2.05	0.00	2.05	2.04	2.08	2.09	**2.15**	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.94	24.00
7068	1.81	1.88	0.00	1.95	0.00	0.00	1.97	2.01	2.03	**2.05**	2.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.98	24.00
7277	2.82	2.93	0.00	3.01	0.00	0.00	0.00	3.11	3.14	3.18	3.12	0.00	0.00	0.00	**3.24**	0.00	0.00	0.00	0.00	0.00	2.99	25.28
7791	4.46	4.62	0.00	4.71	0.00	0.00	4.73	4.88	4.99	5.10	4.99	5.04	4.95	5.12	**5.43**	5.18	4.94	0.00	0.00	0.00	1.24	27.02
7904	3.72	3.91	0.00	4.06	0.00	4.12	4.07	4.14	4.18	**4.25**	4.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.97	24.00

Please cite this article as: Tanner, B.R., et al., Sedimentary proxy evidence of a mid-Holocene hypsithermal event in the location of a current warming hole, North Carolina, USA, Quaternary Research (2014), http://dx.doi.org/10.1016/j.yqres.2014.11.004

based on the pollen curve, which shows a mid-Holocene expansion of grasses coincident with elevated $\delta^{13}C$ values (present in multiple cores), indicating increased C_4 plant abundance. A mid-Holocene increase in grasses is also seen in the pollen profile at nearby Horse Cove Bog (Delcourt and Delcourt, 1997), which indicates that the expansion of C_4 grasses recorded at Panthertown is part of a larger regional trend. Organic biomarker *n*-alkane distributions from the Panthertown wetland show an increase of the C_{18} chain length during the mid-Holocene. C_{18} is a biomarker for bacteria and suggests organic matter breakdown, which would be expected in a warm, dry climate. The terrestrial (upland) pollen recovered from the wetland also shows mid-Holocene environmental change that coincides with the warm, dry mid-Holocene conditions found at the wetland.

There is also evidence for mid-Holocene warm, dry conditions from other sites in the general region that generally coincides with the Panthertown record (Driese et al., 2008; Kocis, 2011; Driese et al., 2012; Li et al., 2012). Although a warm, dry mid-Holocene is likely present in the Southern Appalachians, some proxy records from other regions of the southeastern USA show evidence of wet mid-Holocene conditions (e.g. Goman and Leigh, 2004). Also, as noted in our introduction, the timing of warmer mid-Holocene conditions seems to vary across much of North America.

Our data show that the current southeastern USA "warming hole" is anomalous, not only with respect to the current global warming trend, but apparently also with respect to mid-Holocene warming, which apparently impacted the southeastern USA in the region of the Panthertown site. Although it is not likely the result of increased greenhouse gas concentrations, the mid-Holocene hypsithermal could be viewed as an analog to current and future warm climate conditions and provide insight into earth system responses to such change. Conversely, further comparison of mid-Holocene climate responses to increased Northern Hemisphere insolation caused by Milankovitch cycles to modern climate responses to greenhouse gas forcing can provide useful insight into the varied responses of the climate system to different warming mechanisms and potentially improve the accuracy of climate models.

Acknowledgments

Radiocarbon dates for Panthertown Valley were funded by the United States Forest Service, Southern Research Station, WCU's Program for the Study of Developed Shorelines, and by WCU's Department of Geosciences and Natural Resources. A NOAA grant to WCU also provided funds for field work and analysis. The Nantahala District of the USFS granted access to the site.

References

Albro, P.W., 1976. Bacterial waxes. In: Kolattukudy, P.E. (Ed.), Chemistry and Biochemistry of Natural Waxes. Elsevier, Amsterdam, pp. 419–439.

Alexander, L.V., et al., 2013. Observations: atmosphere and surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Navels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013: the physical science basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 159–254.

Bartlein, P.J., Edwards, M.E., Shafer, S.L., Barker Jr., E.D., 1995. Calibration of radiocarbon ages and the interpretation of paleoenvironmental records. Quaternary Research 44, 417–424.

Birks, H.H., Birks, H.J., 2006. Multi-proxy studies in palaeolimnology. Vegetation History and Archaeobotany 15, 235-215.

Blumer, M., Guillard, R.R.L., Chase, T., 1971. Hydrocarbons of marine plankton. Marine Biology 8, 183–189.

Blundell, A., Barber, K., 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. Quaternary Science Reviews 24, 1261–1277.

Chikaraishi, Y., Naraoka, H., 2003. Compound-specific δD-$\delta^{13}C$ analyses of *n*-alkanes extracted from terrestrial and aquatic plants. Phytochemistry 63, 361–371.

Collister, J.W., Rieley, G., Stern, B., Eglinton, T., Fry, B., 1994. Compound specific $\delta^{13}C$ analyses of leaf lipids from plants with differing carbon dioxide mechanisms. Organic Geochemistry 21, 619–627.

Cranwell, P.A., Eglinton, G., Robinson, N., 1987. Lipids of aquatic organisms as potential contributors to lacustrine sediments. Organic Geochemistry 11, 513–527.

Davidson, T.A., Reid, M.A., Sayer, C.D., Chilcott, S., 2013. Palaeolimnological records of shallow lake biodiversity change: exploring the merits of single versus multi-proxy approaches. Journal of Paleolimnology 49, 431–446.

Delcourt, H.R., 1979. Late Quaternary vegetation history of the Eastern Highland Rim and adjacent Cumberland Plateau of Tennessee. Ecological Monographs 49, 255–280.

Delcourt, H.R., Delcourt, P.A., 1985. Quaternary palynology and vegetational history of the Southeastern United States. In: Bryant Jr., V.M., Holloway, R.G. (Eds.), Pollen Records of Late-Quaternary North American Sediments. American Association of Stratigraphic Palynologists Foundation, pp. 1–37.

Delcourt, H.R., Delcourt, P.A., 1997. Pre-Columbian native American use of fire on Southern Appalachian landscapes. Conservation Biology 11, 1010–1014.

Driese, S.G., Li, Z.-H., McKay, L.D., 2008. Evidence for multiple, episodic, mid-Holocene hypsithermal recorded in two soil profiles along an alluvial floodplain catena, southeastern Tennessee, USA. Quaternary Research 69, 276–291.

Driese, S.G., Li, Z.-H., Cheng, H., Stinchcomb, G.E., Kocis, J.J., Horn, S.P., Boehm, M.S., 2012. Speleothem micromorphology improves interpretations of floodplain paleoclimate records and enhances interpretations of the timing and structure of the mid-Holocene Warm Period. Geological Society of America Abstracts with Programs 44, 303.

Ehleringer, J.R., Cerling, T.E., Helliker, B.R., 1997. C_4 photosynthesis, atmospheric CO_2, and climate. Oecologia 112, 285–299.

Faegri, K., Iverson, J., 1989. Textbook of Pollen Analysis. John Wiley and Sons, Chichester, UK.

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology 40, 503–537.

Ficken, K.J., Li, B., Swain, D.L., Eglinton, G., 2000. An *n*-alkane proxy for the sedimentary input of submerged floating freshwater aquatic macrophytes. Organic Geochemistry 31, 745–749.

Gelphi, E., Schneider, H., Mann, J., Oró, J., 1970. Hydrocarbons of geochemical significance in microscopic algae. Phytochemistry 9, 603–612.

Giger, W., Schaffner, C., Wakeham, S.G., 1980. Aliphatic and olefinic hydrocarbons in recent sediments of Greifensee, Switzerland. Geochimica et Cosmochimica Acta 44, 119–129.

Goman, M., Leigh, D.S., 2004. Wet early to middle Holocene conditions on the upper Coastal Plain of North Carolina, USA. Quaternary Research 61, 256–264.

Goman, M., Leigh, D.S., 2006. Comment on "Holocene aridity and storm phases, Gulf and Atlantic coasts, USA" by Ervin G. Otvos. Quaternary Research 66, 182–184.

Han, B.J., McCarthy, E.D., van Hoeven, W., Calvin, M., Bradley, W.H., 1968. Organic geochemical studies, II. A preliminary report on the distribution of aliphatic hydrocarbons in algae, in bacteria, and in a recent lake sediment. Proceedings of the National Academy of Sciences of the United States of America 59, 29–33.

Huang, Y., Shuman, B., Wang, Y., Webb III, T., Grimm, E.C., Jacobson Jr., G., 2006. Climatic and environmental controls on the variation of C_3 and C_4 plant abundances in central Florida for the past 62,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 237, 428–435.

Indermühle, A., et al., 1999. Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. Nature 398, 121–126.

Jansen, E., et al., 2007. Palaeoclimate. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (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, Cambridge, pp. 433–497.

Johnson, R.W., Calder, J.A., 1973. Early diagenesis of fatty acids and hydrocarbons in a salt marsh environment. Geochimica et Cosmochimica Acta 37, 1943–1955.

Kaufman, D.S., et al., 2004. Holocene thermal maximum in the western Arctic (0–180 degrees W). Quaternary Science Reviews 23, 529–560.

Kocis, J.J., 2011. Late Pleistocene and Holocene hydroclimate change in the Southeastern United States: sedimentary, pedogenic, and stable carbon isotope evidence in Tennessee River floodplain paleosols. (Masters Thesis) The University of Tennessee.

Kornegay, B., 2003. A Guide's Guide to Panthertown Valley. 4th edition. Slickrock Expeditions, Cullowhee, NC.

Kunkel, K.E., Liang, X.Z., Zhu, J.H., Lin, Y.R., 2006. Can CGCMs simulate the twentieth-century "warming hole" in the central United States? Journal of Climate 19, 4137–4153.

LaMoreaux, H.K., Brook, G.A., Knox, J.A., 2009. Late Pleistocene and Holocene environments of the Southeastern United States from the stratigraphy and pollen content of a peat deposit on the Georgia Coastal Plain. Palaeogeography, Palaeoclimatology, Palaeoecology 280, 300–312.

Leigh, D.S., 2008. Late Quaternary climates and river channels of the Atlantic Coastal Plain, Southeastern USA. Geomorphology 101, 90–108.

Lejju, B.J., Taylor, D., Robertshaw, P., 2005. Late-Holocene environmental variability at Munsa archaeological site, Uganda: a multicore, multiproxy approach. The Holocene 15, 1044–1061.

Li, Z.-H., Cheng, H., Driese, S.G., 2012. Episodic drought during mid-Holocene warm period revealed by speleothem carbon and oxygen isotopes and UV fluorescence in southern Appalachians, USA. AGU Fall Meeting Abstract PP21A-1971.

Lichvar, R.W., Butterwick, M., Melvin, N.C., Kirchner, W.N., 2014. The national wetland plant list: 2014 update of wetland ratings. Phytoneuron 2014–41, 1–42.

Liu, Y., Andersen, J.J., Williams, J.W., Jackson, S.T., 2013. Vegetation history in central Kentucky and Tennessee (USA) during the last glacial and deglacial periods. Quaternary Research 79, 189–198.

Loisel, J., Garneau, M., 2010. Late Holocene paleoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: potential and limits of

multi-proxy archives. Palaeogeography, Palaeoclimatology, Palaeoecology 291, 493–533.
Martin, E.M., 2014. Holocene environmental history of Panthertown Valley in the Blue Ridge Mountains of North Carolina. (Master's Thesis) Western Carolina University.
McDonald, J.M., Leigh, D.S., 2011. Terminal Pleistocene through Holocene evolution of Whiteoak Bottoms, a Southern Blue Ridge Mountains peatland. Wetlands 31, 783–797.
Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical Geology 114, 289–302.
Misra, V., Michael, J.P., Boyles, R., Chassignet, E.P., Griffin, M., O'Brien, J.J., 2012. Reconciling the spatial distribution of the surface temperature trends in the southeastern United States. Journal of Climate 25, 3610–3618.
Mullins, H.T., Patterson, W.P., Teece, M.A., Burnett, A.W., 2011. Holocene climate and environmental change in central New York (USA). Journal of Paleolimnology 45, 243–256.
Nordt, L.C., Boutton, T.W., Hallmark, C.T., Waters, M.R., 1994. Late Quaternary vegetation and climate change in Central Texas based on the isotopic composition of organic carbon. Quaternary Research 41, 109–120.
O'Leary, M.H., 1988. Carbon isotopes in photosynthesis: fractionation techniques may reveal new aspects of carbon dynamics in plants. BioScience 38, 328–336.
Otvos, E.G., 2004. Prospect for interregional correlations using Wisconsin and Holocene aridity episodes, northern Gulf or Mexico coastal plain. Quaternary Research 61, 105–118.
Otvos, E.G., 2005. Holocene aridity and storm phases, Gulf and Atlantic coasts, USA. Quaternary Research 63, 368–373.
Otvos, E.G., 2006. Reply to letter to the editor from Goman and Leigh. Quaternary Research 66, 185–186.
Paillet, F.L., 2002. Chestnut: history and ecology of a transformed species. Journal of Biogeography 29, 1517–1530.
Pan, Z., Arritt, R.W., Takle, E.S., Gutowski Jr., W.J., Anderson, C.J., Segal, M., 2004. Altered hydrologic feedback in a warming climate introduces a "warming hole". Geophysical Research Letters 31, L17109. http://dx.doi.org/10.1029/2004GL020528.
Pittillo, J.D., 1994. Natural areas inventory for Jackson County, North Carolina. A Report to the Conservation Trust for North Carolina. Jackson County Department of Planning and Development, State of North Carolina Natural Heritage Program, Raleigh, NC.
Portmann, R.W., Solomon, S., Hegerl, G.C., 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. Proceedings of the National Academy of Sciences 106, 7324–7329.
Reimer, P.J., et al., 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.
Robinson, W.A., Reudy, R., Hansen, J.E., 2002. General circulation model simulations of recent cooling in the east-central United States. Journal of Geophysical Research 107, 4748. http://dx.doi.org/10.1029/2001JD001577.
Schafale, M.P., 2012. Guide to the Natural Communities of North Carolina, Fourth Approximation. North Carolina Heritage Program, Raleigh, NC.
Schafale, M.P., Weakley, A.S., 1990. Classification of the Natural Communities of North Carolina, Third Approximation. North Carolina Heritage Program, Raleigh, NC.
Shafer, D.S., 1988. Late Quaternary landscape evolution at Flat Laurel Gap, Blue Ridge Mountains, North Carolina. Quaternary Research 30, 7–11.
Tanner, B.R., Uhle, M.E., Mora, C.I., Kelley, J.T., Schuneman, P.J., Lane, C.S., Allen, E.S., 2010. Comparison of bulk and compound-specific $\delta^{13}C$ analyses and determination of carbon sources to salt marsh sediments using *n*-alkane distributions (Maine, USA). Estuarine, Coastal and Shelf Science 86, 283–291.
Teeri, J.A., Stowe, L.G., 1976. Climatic patterns and the distribution of C_4 grasses in North America. Oecologia 23, 1–12.
Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. The intercept is a poor estimate of a calibrated radiocarbon age. The Holocene 14, 296–298.
Thein, S.J., 1979. A flow diagram for teaching texture by feel analysis. Journal of Agronomic Education 8, 54–55.
Waller, S.S., Lewis, J.K., 1979. Occurrence of C3 and C4 photosynthetic pathways in North American grasses. Journal of Range Management 32, 12–28.
Wang, X.C., Chen, R.F., Berry, A., 2003. Sources and preservation of organic matter in Plum Island salt marsh sediments (MA, USA): long-chain *n*-alkanes and stable carbon isotope compositions. Estuarine, Coastal and Shelf Science 58, 917–928.
Weakley, A.S., 2012. Flora of the Southern and Mid-Atlantic States. University of North Carolina at Chapel Hill, North Carolina Botanical Garden, UNC Herbarium.
Weete, J.D., 1976. Algal and fungal waxes. In: Kolattukudy, P.E. (Ed.), Chemistry and Biochemistry of Natural Waxes. Elsevier, Amsterdam, pp. 350–404.
Wickstrom, C.W., 1979. Geology of the eastern half of the Blue Ridge Quadrangle, North Carolina. (Master's Thesis) University of New Orleans.

Please cite this article as: Tanner, B.R., et al., Sedimentary proxy evidence of a mid-Holocene hypsithermal event in the location of a current warming hole, North Carolina, USA, Quaternary Research (2014), http://dx.doi.org/10.1016/j.yqres.2014.11.004