A 12,000 Kyr Paleohydroclimate Record in the Southeastern, U.S.A based on Deuterium from Bat Guano

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Abstract

The southeastern United States endures environmental change from human population increase, climate change, and land use alterations creating the need to understand baseline conditions and environmental patterns prior to human impacts. While paleoenvironmental data can be reconstructed from a variety of archives (e.g. lake sediments, tree rings, speleothems), some geographic areas contain fewer of such records. One archive capable of recording moisture regimes and other paleoenvironmental changes over millennia but has received little attention relative to other climate proxies, are bat guano deposits in cave systems. Bat guano deposits are found in many cave environments in the southeastern United States and can be used as an archive of paleoenvironmental data including precipitation, vegetation, and aspects associated with the ecology of bats. Here, we present a 12,000-year record of paleoenvironmental change based on $\delta^2\text{H}$ stable isotopes in a guano core collected from Cave Springs Cave in Alabama, USA. Results suggest distinct shifts in moisture during the lower Holocene/upper Pleistocene (9,551 – 12,131 cal yr BP) ($\delta^2\text{H}$ values -86.82 – -77.70) and during the middle Holocene (3,886 – 9,351 cal yr BP) ($\delta^2\text{H}$ values -125.74 – -80.63), roughly coinciding with the Holocene Climatic Optimum (HCO) time interval (5,000 – 9,000 cal yr BP). During the last 4,000 years, conditions in the region shifted once again in the southeastern United States region. Climate inferences based on guano $\delta^2\text{H}$ are consistent with the role of atmospheric moisture on regional vegetation changes suggested by previous pollen records obtained from lake sediment cores. This study suggests bat guano $\delta^2\text{H}$ may be a reliable method to provide a long-term paleoclimate record.

Introduction

In recent decades, interannual variability in summer precipitation has intensified significantly over the southeastern United States, with an increased frequency of both abnormally wet and dry summers (Wang et al. 2010). Summer rainfall is essential to support agriculture, energy production and the economy of this region (e.g. Manuel 2008; Martinez et al. 2009; Gotvald and McCallum 2010). It is therefore crucial to understand the driver of summer precipitation variability from interannual to multidecadal timescales. It remains unclear the extent to which natural climate varies and climate changes due to the increasing atmospheric concentration of greenhouse gases which controls precipitation fluctuation in the southeastern region of the United States. Regional and global climate models suggest that increasing greenhouse gases can influence summer rainfall patterns in the southeast although the extent to which natural processes versus anthropogenic drivers control rainfall variability remains uncertain (Li et al. 2013).

Paleoclimate and paleoenvironmental records offer the opportunity to investigate the role of natural climate processes on precipitation patterns in the southeastern United States and examine the magnitude of past changes in precipitation and moisture availability. Paleoclimate reconstructions from tree rings, pollen, and lake sediment cores have focused on the polar, temperate, and tropical regions of the globe with fewer records from subtropical areas. The subtropical southeastern United States is home to

environments typically useful for paleoreconstructions (e.g., natural lakes, tree rings), but most records contain short chronologies beginning in the mid Holocene or later (Larson and Schaetzl 2001). Natural lakes in the southeast are uncommon outside of the coastal plain compared to areas in higher latitudes with histories of glaciers and ice sheets. Most paleoclimate data in the southeastern region have resulted from dendrochronology records (Stahle et al. 1998; Stahle et al. 2019) which are limited to the most recent millennia (Therrell et al. 2006) or from coastal-plain lakes (Watts 1971; Watts 1975; Whitehead and Sheehan 1985). Current instrumental data of air surface temperatures and rainfall amount, in addition to tree ring chronologies provide accurate and high-resolution environmental information but do not extend beyond the time interval when the region experienced the first European settlements ~1600s-1700s (Stahle et al. 1998; Cleaveland et al. 2003; Therrell et al. 2006).

Two documented paleoclimate events that have been supported by pollen records from the southeastern United States are the Holocene Climatic Optimum (HCO) and the Hypsithermal Event (Delcourt 1980; Delcourt and Delcourt 1983; Folland et al. 1990; Marcott et al. 2013; Mendieta et al. 2018). Both events were characterized by warm periods from 5000 – 9000 years before present (cal yr BP) that coincided with a transition from *Quercus* spp. (oak) dominance to increased *Pinus* spp. (pine) densities across the southeastern United States landscape as indicated by lake sediment pollen records (Watts 1971; Delcourt 1980; Grimm and Jacobson 1992; Grimm et al. 1993). Additional lake sediment studies have assessed pollen species and abundances to document environmental shifts in vegetation, moisture, and temperature changes over time in the southeast region (Watts 1971; Watts 1975; Filley et al. 2001; Donar et al. 2009). However, few of these studies examined direct moisture regimes from $\delta^{18}\text{O}$ or $\delta^2\text{H}$, which has been used in tropical systems (Curtis et al. 1998; Hodell et al. 1999).

Past climate changes can be reconstructed from lacustrine sediments, ice cores, speleothems, and soils (Grimm et al. 1993; Waters et al. 2009; Medina-Elizalde and Rohling 2012). Isotope time-series from bat guano is one paleoclimate record that effectively tracks moisture regimes but has received less investigation in the southeastern United States (Bird et al. 2007; Wurster et al. 2007; Wurster et al. 2010; Onac et al. 2014; Forray et al. 2015; Wurster et al. 2017; Cleary et al. 2017; Cleary et al. 2018; Cleary et al. 2019). Bat guano cores can be collected from large, undisturbed guano deposits in cave environments and can be a useful archive for paleoclimate reconstructions (Bird et al. 2007; Wurster et al. 2007; Onac et al. 2014; Forray et al. 2015; Cleary et al. 2016; Campbell et al. 2017; Cleary et al. 2018; Cleary et al. 2019). Guano cores are suitable for study from caves with constant or seasonal bat presence and ideally from areas within the caves that have remained largely isolated from surficial weathering processes (e.g. low ventilation) and human disturbances (Onac et al. 2014; Cleary et al. 2016). In the southeastern United States, unfortunately, these types of deposits are rare since guano mining for the production of gunpowder, particularly during the Civil War, depleted the largest/oldest deposits (Hubbard 2019). Many bat species in the southeastern United States migrate seasonally to caves elsewhere, making guano deposits within a single cave seasonally specific (Wurster et al. 2008; Cleary et al. 2016). Previous studies have shown that guano cores record past environmental conditions from an array of climates including tropical, semi-arid, and temperate (Wurster et al. 2017; Campbell et al. 2017; Cleary et al. 2019). When

present, guano deposits can provide largely undisturbed depositional environments that can be radiocarbon dated (Onac et al. 2013; Wurster et al. 2017). Primary analyses that have been applied to guano deposits include stable isotopes (Wurster et al. 2008; Wurster et al. 2010), organic matter (Shahack-Gross et al. 2004; Campbell et al. 2017), pollen (Maher 2006; Geantă et al. 2012; Campbell et al. 2017), elements such as magnesium, calcium, phosphorous, iron (Giurgiu and Tămas 2013), and nutrients (Hill et al. 1997; Giurgiu and Tămaş 2013).

Bat guano research has been primarily conducted in the southwestern United States (Wurster et al. 2008; Wurster et al. 2010), the Caribbean (Mizutani et al. 1992a, b; McFarlane et al. 2002; Gallant et al. 2020), Romania (Giurgiu and Tamas 2013; Onac et al. 2014; Forray et al. 2015; Cleary et al. 2016; Cleary et al. 2018; Cleary et al. 2019), and southeast Asia (Bird et al. 2007). Therefore, the southeastern region of the United States is lacking in guano studies, despite having a large density of caves (over 3,000 in the Appalachian region and over 2,300 in Alabama) (Culver et al. 1999; Culver et al. 2006) and roosting bat hibernacula. Currently, only two guano core studies have been published in this region (Campbell et al. 2017; Tsalickis et al. Accepted Manuscript). Given the need for paleoreconstructions in the non-coastal southeastern United States, we analyzed $\delta^2\text{H}$ values as well as elements, and nutrients from a guano core collected at Cave Springs Cave in northern Alabama (Figure 1) to provide one of the longest records of paleoclimate and paleoenvironmental change for the southeastern United States. Here, we expand upon data described in Tsalickis et al. (Accepted Manuscript). The guano core spanned the Holocene time interval (last 11,650 cal yr BP) and was collected from a maternal colony of gray bats (*Myotis grisescens*) that roost in this cave during summer months. From this data, we inferred changes in precipitation and climate patterns from $\delta^2\text{H}$ (Deuterium) via bulk guano over the Holocene. Three objectives were investigated: 1) to establish a dated record of isotopic chemistry and precipitation patterns from northern Alabama, 2) to compare the Cave Springs Cave guano record to other paleoclimate records in the southeastern United States in order to examine their regional context, and 3) to determine environmental drivers of isotopic changes in guano for $\delta^2\text{H}$ over time.

Methods

Study site and core collection

Cave Springs Cave is located in northern Alabama near the city of Priceville (34.5251° N, 86.8947° W) and is part of the Wheeler National Wildlife Refuge (Figure 1). Cave Springs Cave is 3,371 meters in total length and is well mapped. The dominant bat species occupying the cave is the gray bat (*Myotis grisescens* Howell). The guano pile was ~ 2 meters above the cave floor and was cored approximately 487 meters from the entrance. The core was retrieved in two sections of polyvinyl chloride (PVC) pipe hammered into the pile with a mallet totaling around 87 cm compacted and 183 cm uncompacted. To prevent overlap and disturbance between the core sections, the guano pile was removed while the first section was intact so that the beginning of the second section was undisturbed forming one continuous

core. Core sections were returned to the lab, stored in a freezer at 0°C, and were later sectioned at 1 cm intervals.

Based on available climate data from the Priceville meteorological station, the present-day climate of the area can be characterized as humid subtropical, with no seasonality in precipitation and monthly averages ~ 107 millimeters of rain for 2018. the annual temperature fluctuates between 10°C-32°C. Various factors have been invoked to influence summer precipitation variability in the southeastern United States, including sea surface temperatures (SSTs) and associated atmospheric circulation anomalies (Wang and Enfield 2001; Seager et al. 2003; Schubert et al. 2009; Kushnir et al. 2010), hurricane activity (Elsner and Tsonis 1993; Chan and Misra 2010), soil moisture (Koster et al. 2004; Wu et al. 2007, Wei et al. 2016) and the subtropical high over the North Atlantic (Katz et al. 2003). On interannual to decadal time scales changes in the intensity and position of the North Atlantic subtropical high (NASH) has been linked to precipitation and intensity of drought in the southeastern United States (Li and Li 2011). Studies have recently suggested that the position and intensity of the NASH and moisture flux convergence are major drivers of precipitation variability in the southeastern region (Li and Li 2011; Li et al. 2013, Wei et al. 2016).

Gravimetric analysis, nutrients, and isotopes

Guano core sections were analyzed gravimetrically for bulk density and organic matter. For bulk density, 5 cm³ of raw guano from each 1 cm interval was weighed, dried, and processed similarly to lake sediments (Brenner and Binford 1988; Campbell et al. 2017). Dried samples of bulk guano from each 1 cm interval were burned at 550°C for three hours and organic matter was reported as percent loss on ignition (LOI). Bulk density is reported as g dry cm⁻³ wet.

Total phosphorus (P), sulfur (S), and other nutrients (Ca, Fe, Mg, K, Al, Na, S) were measured from dried sediments using an ARL 3560 ICP-AES following complete acid digestion using standard EPA methods (Waters et al. 2009). Total organic carbon (TOC) and total nitrogen TN were measured using a Costech Combustion Elemental Analyzer with an attached auto-sampler. Prior to analysis, samples were acidified for 12 hours in HCl vapors to remove inorganic carbon.

For $\delta^2\text{H}$ analysis, bulk, freeze-dried guano from each 1 cm interval was weighed (~1 mg) and folded in tin sample capsules using a Mettler Toledo XPR2U microbalance and sent to the Cornell University Stable Isotope Laboratory (<http://www.cobsil.com/>, Ithaca, New York, USA). Deuterium isotopic measurements were calculated using an isotope ratio mass spectrometer (IRMS) relative to an internal standard and calibrated to the international reference standard of V-SMOW (Vienna Standard Mean Ocean Water). The standard is an average of different ocean water samples around the world:

$$\delta^2\text{H} (\text{‰}) = \left[\frac{\frac{D}{H_{\text{sample}}}}{\frac{D}{H_{\text{VSMOW}}}} - 1 \right] \times 1000 \quad (1)$$

Radiocarbon dating

Approximately one gram of guano was sampled from 25, 36, and 51 cm depths in the core. Depths were chosen visually where abrupt color changes were found. All samples were dried for 24 hours in a drying oven and sent to the Center for Applied Isotope Studies, University of Georgia (Athens, Georgia, USA) for Accelerator Mass Spectrometry (AMS) ¹⁴C analysis. AMS ¹⁴C ages were calibrated using the IntCal13 calibration curve as part of the BACON model package in R which uses Bayesian based modelling statistics (Blaauw and Christen 2011) (Table I). To calculate ages for depths where ¹⁴C measurements were unavailable, the core top was marked as the date of collection and the uncalibrated ¹⁴C dates were incorporated into the BACON model package in R.

Table I

¹⁴C dates from Cave Springs Cave in Priceville, Alabama and their respective isotope values. ¹⁴C dates are in stratigraphic order

Depth (cm)	¹⁴ C Cal (cal yr BP)	¹⁴ C Age (cal yr BP)	UGAMS#
25	4570 ± 20	4070 ± 20	35051
36	6351 ± 25	5560 ± 25	35052
51	9151 ± 50	8190 ± 50	34438

Statistical analyses

Distinctions between lower Holocene/upper Pleistocene (9,551 – 12,131 cal yr BP), middle (3,886 – 9,351 cal yr BP), and late (0 – 3,715 cal yr BP) Holocene were chosen utilizing the δ²H measurements from the guano core. A Kruskal-Wallis non-parametric AOV was used for each isotope system using Statistix 9.0, Analytical Software (Tallahassee, FL). A Principal Component Analyses (PCA) was performed on H² isotopic values as well as elemental concentrations (Fe, Al, K, Ca, P, Mg) in order to determine the ordination of δ²H and elements throughout each Holocene period. PCA was conducted using R statistical software.

Results

Core description and age

The Cave Springs Cave guano core was 87 cm in total length when compacted and the area cored from did not show any visual signs of anthropogenic or biological disturbance (e.g., foot traffic and mining). Based on microscopic analysis, the Cave Springs Cave guano core consisted of chitinous insect pieces, bat hair, and fecal material. The bottom of the core was lighter in color and densely packed with clay-like consistency, while the top of the core had recent guano deposits and was dark brown in color with pellet-like consistency (Figure 2). Between 87-67 cm, guano was not observed. Instead, this section of the core was inferred to be the mineral brushite, due to the lack of organic matter and high percentages of P and Ca which are characteristic of brushite found in other guano cores (Giurgiu and Tamas 2013; Onac et al. 2015). Given the objectives of the study, the brushite part of the core (87-67 cm) was not included in the paleoreconstructions (Giurgiu and Tamas 2013). From 66 cm to 42 cm, the guano showed light tan striations. Starting at 41 cm depth, the guano was consolidated and became lighter in color through 28 cm (Figure 2). The top portion of the core (0-27 cm) was dark brown in color with pellet-like guano (Figure 2).

The Cave Springs Cave guano core provided a dated record of environmental change from present day to $9,151 \pm 30$ cal yr BP at 51 cm based on calibrated AMS ^{14}C dates and a BACON model projected age of $\sim 12,000$ cal yr BP at 66 cm (Figure 3). The measured AMS C^{14} dates along with the top of the core were fitted with a best-fit line ($r^2=0.99$), a slope of $y=0.0054X + 0.3415$, and minimal age uncertainty (± 20 -50 years), suggesting constant deposition throughout the Holocene period.

Elements and nutrients

Organic matter was measured as loss on ignition (LOI) and generally increased up the core (Figure 4). Organic matter content was the highest at 66 cm (71%) and the lowest 20 cm (22%). Bulk density decreased up the core from 66-22 cm corresponding to depth and compaction of the guano through time (Figure 4). Total carbon (TC) increased up the core, containing minimal values of 1.1% at 66 cm and a peak value of 39.4% at 3 cm. Total nitrogen (TN) followed the same pattern of increasing up the core and a peak value of 9.1% at 9 cm. Calcium and Phosphorus both were the highest in concentration at the bottom of the core with values of 90.53 mg/g and 54.24 mg/g, respectively. Calcium was most concentrated at 37 cm as well (7,500 cal yr BP) while Phosphorus peaks at 57 cm ($\sim 12,000$ cal yr BP) (Figure 4).

$\delta^2\text{H}$ isotopes

Between 66-53 cm, the $\delta^2\text{H}$ values were consistently heavier averaging -79.9 ‰, whereas between 10,916 cal yr BP and 4,177 cal yr BP, $\delta^2\text{H}$ values were lighter averaging -116.3 ‰ (Figure 5). From 4,177 cal yr BP

to present day, $\delta^2\text{H}$ values are again heavier (-77.69 ‰). The transition from middle to the upper Holocene is marked as a pronounced positive shift in $\delta^2\text{H}$.

There were significant differences between upper, middle, and lower Holocene time periods for $\delta^2\text{H}$ ($\chi^2 = 38.8$, $p = 0.001$). Lower Holocene/upper Pleistocene and upper Holocene were not statistically different based on $\delta^2\text{H}$, whereas middle Holocene was significantly different compared to the lower Holocene/upper Pleistocene and upper Holocene based on $\delta^2\text{H}$. The PCA confirmed that there were three distinct time periods (lower Holocene/upper Pleistocene, middle, and upper Holocene) ordinated differently from each other with 77.5% of the dataset's variance accounted for by PC1 and PC2 (Figure 6).

Discussion

Dating record

Based on the BACON dating calculations, the Cave Springs Cave guano core spanned the last ~12,000 cal yr BP and constitutes the oldest guano core environmental record from the southeastern United States. It is important to address only three radiocarbon dates were used to construct the model, however other studies reconstructing paleoclimate utilizing bat guano have also used three or less radiocarbon dates (Bird et al. 2007; Wurster et al. 2010; Onac et al. 2014; Cleary et al. 2016). The comparison of radiocarbon dates between guano core studies has been described in Tsalickis et al. (Accepted Manuscript). The calibrated radiocarbon ages contain multiple paleoclimatic events in this region. The Hypsithermal event occurred 5000-9000 cal yr BP and has been characterized by a warmer environment (Delcourt 1980; Delcourt and Delcourt 1980; Driese et al. 2008; Tanner et al. 2015). The HCO occurred at the same time (5000-9000 cal yr BP) and is characterized by increases in *Quercus* spp. transition from *Pinus* spp. and a moisture shift from dry to wet conditions, inferred from pollen (Frey 1953; Watts 1970; Delcourt and Delcourt 1980; Watts and Hansen 1994). Unlike other sources of paleo data (e.g., lake sediment cores, ice cores) guano cores contain few disturbances related to climate, bioturbation, or redox alteration (Onac et al. 2014; Cleary et al. 2016). The cavern where the guano pile occurred did not show signs of historic flooding or water disturbance as noted in other areas of the cave. As a result, the bat colonies are assumed to have maintained a consistent migratory pattern with summer roosting and did not interact with the guano piles below the roosting areas.

Elemental changes

Calcium has the highest concentrations (>80 mg/g) in the early middle Holocene to lower Holocene while Phosphorus has higher concentrations (> 40 mg/g) in the lower Holocene/upper Pleistocene. Bird et al. 2007 also documented an increase in phosphorus concentrations in the older portion of his bat guano core, calcium however, was not measured. Phosphate minerals are common in caves containing bat guano and form due to reactions between guano and clay minerals in acidic conditions (Giurgiu and Tămaş 2013). This could explain why phosphorus and calcium concentrations are highest in the oldest

portion of the Cave Springs Cave core – more time allows for phosphate minerals such as brushite, hydroxylapatite, or variscite to form through digestion, dissolution, double replacement, and redox reactions (Onac and Forti 2011; Giurgiu and Tămaş 2013). Additionally, there are few studies that have examined minerals from bat guano deposits in caves (Fiore and Laviano 1991; Dumitraş et al. 2002; Dumitraş et al. 2004; Onac et al. 2004; Marincea et al. 2006; Frost and Palmer 2011).

Deuterium evidence

Hydrogen (H) isotopes can undergo fractionation through evaporation, condensation, and precipitation as well as through trophic interactions (Schimmelmann and DeNiro 1986; Gröcke et al. 2006; Wurster et al. 2008; Wurster et al. 2010; Peters et al. 2012). According to Peters et al. (2012), evaporation favors light isotopes therefore, the water in the bodies of animals, and in this case bats, tends to be deuterium enriched. This causes trophic enrichment of H^2 as the H incorporated into animal tissues is from an enriched source. When considering this mechanism in insectivorous bat guano, there is a three-tier or four-tier trophic system possible (plant tissue, insect chitin, bat guano) or (plant tissue, plant-eating insect, carnivorous insect, bat guano) allowing H^2 to become enriched by the time it is deposited in bat guano (Gröcke et al. 2006; Onac et al. 2014; Cleary et al. 2016). H^2/H^1 ratios have frequently been used as measures of paleoclimate (Birchall et al. 2005) despite a lack of understanding trophic discrimination of H isotopes between resources and consumer tissues (Peters et al. 2012). Many paleoclimate studies utilizing bat guano have also not incorporated H^2 isotope fractionation through trophic levels into their interpretation (Bird et al. 2007; Onac et al. 2014; Forray et al. 2015; Choa et al. 2016; Cleary et al. 2016). Wurster et al. (2010) is the first guano study that has applied effects of H^2 isotopic fractionation in their guano cores via labile hydrogen exchange with atmospheric H_2O and reported H^2 values from their study fall between -188‰ to -143‰.

Hydrogen isotopic fractionation is a process that was not considered in this study and is also not often considered in other bat guano studies reconstructing paleoclimate (Bird et al. 2007; Onac et al. 2014; Forray et al. 2015; Choa et al. 2016; Cleary et al. 2016). One reason δ^2H is not often considered in bat guano studies is due to its high vulnerability to error. δ^2H profiles can be highly influenced by degradation or contamination, or environmental effects (Wurster et al. 2010). It is accepted that bat guano δ^2H reflects shifts in moisture source or precipitation amount (Wurster et al. 2008; Wurster et al. 2010), but interpretation is lacking. According to the interpretation of Wurster et al. 2010, lighter δ^2H values reflect higher precipitation while heavier δ^2H values indicate more aridity. Using the δ^2H values from Cave Springs Cave and based on our statistical analysis, we are not interpreting between wet versus dry periods, but instead indicating that there are three distinct shifts in moisture for the region: 1) the upper Holocene (0 – 4,000 cal yr BP), 2) the middle Holocene (4,000 – 10,000 cal yr BP), and 3) the lower Holocene/upper Pleistocene (11,000 – 12,000 cal yr BP).

$\delta^2\text{H}$ and pollen comparisons

Pollen records from locations in northwest Georgia, Alabama, Florida, South Carolina, and North Carolina (Frey 1953; Watts 1971; Watts 1975; Delcourt 1980) provide evidence for a hypsithermal event in the southeastern United States occurring between 9000 and 5000 cal yr BP (Delcourt 1980; Delcourt and Delcourt 1980; Whitehead and Sheehan 1985). The hypsithermal event is coeval with persisting negative guano $\delta^2\text{H}$ values interpreted to reflect a wet period. Pollen records also provide evidence for the HCO which has been frequently observed in previous cores collected from lake sediments across the Gulf Coastal Plain (Frey 1953; Watts 1970; Watts 1971; Watts 1975; Delcourt 1979; Delcourt and Delcourt 1980; Whitehead and Sheehan 1985; Watts and Hansen 1994). Additionally, *Quercus* is at its maximum and *Pinus* at its minimum from 9000 to 5000 cal yr BP and this was apparent in lake sediment cores from Bartow County, Georgia, USA (241 km east of Priceville, Alabama) when pine began to dominate about 5000 cal yr BP and replaced oak forests during the upper Holocene (Figure 7). Thus, the *Quercus* to *Pinus* shift would also be expected to have occurred in northern Alabama with the most likely explanation for this shift to be a change in precipitation. *Pinus* are better adapted to drier environments (Watts 1971; Watts 1975; Delcourt 1980; LaMoreaux et al. 2009), allowing them to thrive for the last 4000 years since this is when an inferred decrease in moisture in the Cave Springs Cave $\delta^2\text{H}$ record is observed. *Quercus* dominated from 10,000 – 4,000 cal yr BP due to wetter conditions (Delcourt 1980; Watts and Hansen 1994), which is also supported by the Cave Springs Cave $\delta^2\text{H}$ record.

It is important to take into consideration that pollen may yield different results than bat guano. Pollen producing vegetation can respond to additional environmental factors such as temperature, topography, soil type, and reproductive patterns. $\delta^2\text{H}$ stable isotopes provide a direct measure of moisture, which could cause stratigraphic differences from pollen alterations due to temperature. Furthermore, regional climate differences could cause variations in paleoclimate signals as has been shown from the studies previously mentioned as well as new charcoal records from Florida (Mendieta et al. 2018).

Paleoenvironmental studies based on stable isotope records from wetland and sediment cores disagree on the dominant climate regimes in the southeastern United States across the Holocene. Lake sediment cores from east Georgia, Florida, and the North Carolina and Georgia coastal plains provide evidence for a wet climate during the lower Holocene/upper Pleistocene to middle Holocene (Leigh 2008; Filley et al. 2001; Goman and Leigh 2004; and LaMoreaux et al. 2009), while other studies utilizing sediment and wetland cores interpret the upper to middle Holocene as being a dry period (Delcourt 1979; Driese et al. 2008; Tanner et al. 2015). Other pollen records also support a wet climate during the upper to middle Holocene time period (Watts and Hanson 1994; Goman and Leigh 2004; and LaMoreaux et al. 2009). Whitehead and Sheehan (1985) describe the middle to lower Holocene as being a dry period and attribute the cause to changes in lightning induced fire frequency and anthropogenic changes in land use to southern Florida. The $\delta^2\text{H}$ guano record reported here is inferred as being linked to precipitation alone, thus differences between pollen and $\delta^2\text{H}$ stratigraphies are not surprising given the lack of additional

environmental factors recorded in guano. An accepted consensus has not been achieved and additional records are needed to provide a regional pattern.

Conclusions

The bat guano core from Cave Springs Cave in northern Alabama provided a well-dated record of paleoclimate and paleoenvironmental change throughout the Holocene for the summer roosting bat colony. Radiocarbon data revealed this core to be the oldest in the region, providing the longest guano record for the southeastern United States. The most reliable proxy from the Cave Springs Cave core was $\delta^2\text{H}$ stable isotopes. Although hydrogen isotope fractionation was not applied to this study (as in other studies), we believe our data supports shifts which corresponded to moisture changes during the upper, middle, and lower Holocene. In addition, the HCO was determined to be a wetter period, with the deuterium record following closely to the nearby pollen record of Bartow County, Georgia (Watts 1970). Growing research has proven bat guano to be an effective tool for paleoenvironmental reconstructions as it provides a robust and complex resource for interpreting past local climates. In areas of the United States that contain caves with roosting bat colonies (e.g. southeastern United States), bat guano can be an important and promising proxy to use for paleoclimate reconstruction of the local area as well as the broader region.

Declarations

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Conflicts of interest

Authors declare they have no conflict of interest.

Availability of data and material

Data will be made available.

Code availability

Not applicable.

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Figures

Figure 1

Map of Southeastern United States showing Cave Springs Cave. Cave Springs Cave (blue dot) is located on Wheeler National Wildlife Refuge in northern Alabama. The city in closest proximity to the cave is Priceville, Alabama. Green dot represents location of pollen record used to compare to the deuterium record in Bartow County, Georgia. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Cores retrieved from Cave Springs Cave. A) The top 0-32 cm the portion of the core is pellet-like and dark brown. B) The bottom 33-87 cm portion of the core has many colored striations with layers of brushite intermixed with the guano. Guano core was 87 centimeters in total length. * indicates the calibrated radiocarbon AMS date while other dates are from the BACON model

Figure 3

BACON age-depth model for Cave Springs Cave. Blue shaded regions indicate actual ¹⁴C dates obtained. Gray area indicates projected years to a 95% confidence interval. Red line indicates the correlation

Figure 4

Elements and Nutrients of Cave Springs Cave. Bulk density (expressed as dry/wet) increases with depth. TC and TN decrease with depth. Loss on ignition (LOI) decreases with depth. Both elements rapidly increase at the bottom of the core, but at different times. Calcium peaks at 7,908 cal yr BP and phosphorus peaks at 11,121 cal yr BP indicating brushite

Figure 5

$\delta^2\text{H}$ values of Cave Springs Cave guano core from 12,000 cal yr BP to present

Figure 6

Principal Component Analysis of isotope systems ($\delta^2\text{H}$) and elemental concentrations (Fe, Al, K, Ca, P, Mg) in the Cave Springs Cave guano core. D represents $\delta^2\text{H}$. Three distinct time periods are revealed (upper Holocene, middle Holocene, and Lower Holocene/Upper Pleistocene)

Figure 7

Quercus and Pinus pollen record from small ponds in Bartow County, Georgia (Watts 1970) compared to the deuterium record from Cave Springs Cave. The units of measurement for Quercus and Pinus are number of individual specimens (NISP). The gray shaded region indicates the Holocene Climatic Optimum (9000-5000 cal yr BP)

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