A stable isotope and macro-charcoal sediment record spanning the Pleistocene-Holocene transition from Maple Pond in the southern Shenandoah Valley, Virginia, USA

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Keywords: paleoecology, Shenandoah Valley, stable carbon isotopes, charcoal, fire history, Holocene, sinkhole, wetland, sediment core, Virginia, Appalachians

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ABSTRACT

This study presents a paleoenvironmental analysis of a 147-cm sediment core from Maple Pond, a sinkhole pond within the Shenandoah Valley Sinkhole Pond complex at the base of the Blue Ridge in central Virginia. The results document more than 15,000 years of continuous sediment accumulation, fire history, and environmental variability from the Late Pleistocene to the present. Stable carbon isotope ratios ($\delta^{13}C$: -29‰ to -27‰) and atomic C:N ratios (11-36) indicate terrestrial C_3 vegetation as the primary source of organic matter during the Late Pleistocene and early Holocene (15,000–8,000 cal yr BP), followed by a transition toward nitrogen-rich aquatic and wetland inputs during the mid-to-late Holocene. Loss-on-ignition analysis records organic content rising from ~10% in basal sediments to 35–40% in the upper core, reflecting a transition from minerogenic deposition to sustained organic accumulation. Macroscopic charcoal concentrations reveal a mid-Holocene maximum (40–49 cm depth; ~6,000–5000 cal yr BP), attributed to increased regional fire activity, possibly related to warmer drier conditions during the Mid-Holocene Maximum and a shift to fire-adapted forest (oak, hickory, pine). A smaller charcoal peak between 120 and 130 cm may relate to rapid warming at the end of the Younger Dryas, a shift back to cold conditions around 12,000 years ago. The predominance of lower charcoal abundance (<100 fragments/cm3) characterizing the majority of the sequence suggests a long record of frequent, low-intensity fire regimes characteristic of presettlement fire-adapted Appalachian forests. Geochemical and fire history patterns at Maple Pond demonstrate broad consistency with paleoenvironmental reconstructions from nearby sites (Browns Pond, Spring (aka Hack) Pond, Twin Pond and Cranberry Glades), supporting the interpretation that sinkhole ponds and wetlands throughout the Shenandoah Valley underwent similar environmental evolutions across major Late Quaternary climatic transitions.

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GENERAL AUDIENCE ABSTRACT

Understanding how past landscapes and ecosystem changes can inform predictions of future climate responses requires the examination of long-term environmental records. This study analyzes a 147 cm sediment core from Maple Pond, a sinkhole wetland in Augusta County, Virginia, within the Shenandoah Valley. Chemical analysis and charcoal measurements from sediments spanning more than 15,000 years document environmental history from the end of the last Ice Age to the present. Results reveal changing plant communities through time. Between 15,000 and 8,000 years ago, forests dominated the surrounding landscape, and most organic material in the pond emerged from land plants. Over the past 8,000 years, wetland and aquatic plants have contributed increasingly to sediment composition, indicating a transition to a more productive wetland system. Charcoal preserved in sediments was also examined to understand the history of fires in this area. Consistent macrocharcoal levels throughout most of the sequence likely reflect low-intensity fires, likely occurring at intervals of several hundred to a thousand years. A notable charcoal peak between 5,000 and 6,000 years ago may indicate a period of increased fire activity associated with warmer, drier conditions during the mid-Holocene. Patterns observed at Maple Pond parallel those from nearby sites, suggesting that sinkhole wetlands across the Shenandoah Valley experienced comparable environmental changes over millennia. This research highlights the importance of small wetlands serving as natural records of past environmental conditions.

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Introduction

The Holocene history of vegetation dynamics and its climatic and anthropogenic influences within the Great Appalachian Valley of eastern North America have yet to be completely explored. Increases in sedimentary charcoal and alterations in pollen assemblages have been interpreted by some scholars as indicators of indigenous fire management (Delcourt & Delcourt 1997; Fowler& Konopik 2007), while other perspectives point to climate as the predominant regulator of vegetation dynamics and fire activities within the unglaciated Appalachian region (Lafon & Quiring 2012; Flatley et al. 2013). Disentangling the influences of climate-driven fire regimes from indigenous burning practices, which intensified across the eastern woodlands over the last 4,000 years (Nowacki & Abrams, 2008), remains an interpretive challenge that requires high-resolution, multi-proxy paleoenvironmental records.

Analyses of sedimentary organic matter composition from lacustrine and wetland repositories across the eastern United States have documented temporal variations in the relative contributions of terrestrial versus aquatic carbon sources over time (Meyers & Ishiwatari, 1993; Kneller & Peteet 1999). These geochemical signatures provide constraints on vegetation composition and watershed processes that complement conventional pollen-derived reconstructions. Stable carbon isotope ratios ($\delta^{13}C$) of bulk sedimentary organic carbon reflect the isotopic composition of contributing plant sources, with C_3 dominated temperate woodlands yielding distinctly more ^{13}C depleted values (-26‰ to -30‰) compared to C_4 grassland (-10‰ to -14‰) or aquatic productivity (Meyers and Lallier-Vergès, 1999). Although select proxy records from eastern North America exhibit evidence of vegetation transitions during climatic shifts such as the Younger Dryas (12.9-11.7 ka BP; Fastovich et al. 2020), mid-Holocene thermal maximum (8-5 ka; Shuman et al., 2009), the Medieval Climate Anomaly (MCA; 900-1300 CE), and the Little Ice Age (LIA; 1300-1850 CE) (Pederson et al., 2005; Cronin et al., 2010), other studies suggest that central Appalachian woodlands maintained relatively stable vegetative assemblages in spite of millennial-scale climatic variabilities (Driese et al., 2005). Considering the spatial and temporal complexity of vegetation responses to Holocene climatic shifts within the Appalachian region, geochemical proxy records from individual sites remain vital for characterizing local environmental histories.

In contrast to $\delta^{13}C$ values alone, the integrated analytical approach of combining carbon isotope compositions with elemental carbon-to-nitrogen ratios (C:N) provides enhanced differentiation of organic matter sources in lacustrine depositional systems (Meyers & Ishiwatari, 1993). Aquatic algae and phytoplankton assemblages, characterized by protein-rich concentrations and lignin-poor contents, exhibit C:N ratios less than 10, while lignin-rich terrestrial plants have C:N ratios exceeding 20 (Meyers 1994). Heterogeneous organic matter sources, including emergent macrophytic species, wetland vegetation, and degraded terrestrial materials, produce intermediate C:N values (10-20) that introduce ambiguities in source attribution (Kaushal & Binford, 1999). Multi-proxy studies conducted throughout the northeastern United States have documented temporal transitions from terrestrial-dominated organic matter to aquatic-dominated deposition during intervals of enhanced lake productivity (Tanner et al., 2015; Menking et al., 2012), patterns potentially reflecting climatically controlled modifications in watershed hydrological regimes and nutrient delivery. The application of $\delta^{13}C$ versus C:N biplot analysis to sedimentary sequences, following conceptual frameworks established by Meyers and Lallier-Vergès (1999) and subsequently refined, enables systematic tracking of organic matter provenance through time.

The attribution of charcoal accumulation resulting from local fire occurrences versus watershed remobilization of older charcoal material has emerged as a critical issue in Appalachian paleofire studies (Lafon et al., 2017). Macroscopic charcoal particles incorporated within sediments provide unambiguous evidence of past biomass burning, however, their interpretation requires critical consideration of taphonomic processes that may decouple charcoal deposition from contemporaneous fire activity (Vachula et al., 2024; Higuera et al., 2007). This interpretative challenge gains particular relevance in karst physiographic settings where episodic destabilization may transport older material into sinkhole basins.

Sinkhole wetlands developed within karst terrain constitute valuable yet underutilized paleoenvironmental repositories in the central Appalachians. These closed-basin systems, originating from the dissolution of carbonate substrata (limestone and dolomite), amass sediment continuously across millennial timescales with minimal erosional perturbation (Buhlmann et al., 1999; Hettwer et al., 2003). The sinkhole pond complex of the Maple Flats region in Augusta County, Virginia, located on the western slope of the Blue Ridge within the Valley and Ridge physiographic region encompasses one of the most ecologically consequential wetland complexes within the Shenandoah Valley (Fleming and Van Alstine, 1999; Roble 1999). The convergence of closed-basin hydrology, continuous sediment accumulation, and responsiveness to watershed inputs positions these sinkholes as high-resolution recorders of local-to-regional environmental change (Craig et al., 1969). Unlike the open-lake systems characterized by inlet-outlet hydrodynamics, sinkhole wetlands merge signals derived from direct precipitation, surface runoffs, and groundwater inflow, providing spatially constrained records of catchment conditions over time.

The different scientific explanations for long-term vegetation and fire patterns throughout the Appalachian region, encompassing climate forcing mechanisms (Shuman & Marsicek, 2016), indigenous land management practices (Delcourt & Delcourt, 1997), megafaunal extinction impacts (Gill et al., 2009), and successional development patterns (Nowacki & Abrams, 2008), emphasizes the need for additional high-resolution, multi-proxy analysis of continuous sediment accumulation across the Late Pleistocene through Holocene intervals. Multi-proxy analysis of sediment cores derived from sinkhole lakes distributed across the broader Appalachian region have generated comprehensive reconstructions of vegetation, climate dynamics and fire regimes from thousands to tens of thousands of years (Watts, 1979; Kneller & Peteet, 1993, 1999). However, limited investigations within the central Shenandoah Valley have employed combined geochemical proxies ($\delta^{13}C$, C:N, loss-on-ignition) and charcoal proxy analysis at sufficient resolutions for characterizing organic matter source variability alongside fire history.

This study presents a 15,000-year multi-proxy paleoenvironmental reconstruction derived from Maple Pond, a permanent sinkhole wetland situated within the Maple Flats complex of Augusta County, Virginia. The use of stable carbon isotope ratios ($\delta^{13}C$), atomic C:N ratios, loss-on-ignition assessment, and macroscopic charcoal concentration analysis from a continuously accumulated sedimentary sequence, we address the following research objectives (1) Can carbon isotope signatures effectively document historical shifts in organic matter sources, distinguishing terrestrial C_3 vegetations form aquatic or wetland contributions across the Late Pleistocene and

Holocene? (2) What relative contributions did climate variability and fire dynamics exert in shaping vegetation compositions and depositional patterns within the Maple Pond area? (3) How do the geochemical and fire archives from Maple Pond correspond with regional paleoenvironmental syntheses in the central Appalachian region? Our findings contribute new high-resolution proxy evidence from a previously understudied site and provide more insight into the prolonged ecological resilience of the sinkhole pond ecosystem in the Shenandoah Valley.

Study Area

Physical Setting

Maple Pond (37°57'57"N 78°57'51"W; elevation 478 m) is a permanent (year-round vs. vernal) sinkhole pond located in the Maple Flats pond complex of Augusta County, Virginia (Buhlmann et al., 1999) and also a part of the greater Shenandoah Valley Sinkhole Complex (SVSC) The pond is situated near the base of the western slope of the Blue Ridge Mountains within the Valley and Ridge Province on private property adjacent to the George Washington National Forest. Maple pond occupies a closed karst depression created by dissolution of Cambrian age carbonate bedrock (limestone and dolomite) that underlies much of the landscape of the Maple Flats (Mitchell et al., 1999). Overlaying the carbonate bedrock are colluvial and alluvial deposits composed of poorly sorted Antietam quartzite cobbles and boulders within a matrix of sand, silt, and clay (Fleming and Alstine, 1999). These surficial materials were eroded from the adjacent Blue Ridge Mountains and deposited as alluvial fans and colluvial aprons during the late Pleistocene, when periglacial conditions ignited intense weathering and mass wasting on Blue Ridge slopes (Eaton et al., 2003). The Maple Flats complex lies at the base of the one such alluvial fan. The accumulation of acidic quartzitic colluvium over soluble carbonate bedrock creates the unique hydrogeologic and edaphic conditions characteristic of the Shenandoah Valley sinkhole pond system (Fleming and Van Alstine, 1999).

Maple Pond is roughly circular in morphology with a diameter of approximately 74 m (Buhlmann et al., 1999). With a maximum water depth of approximately ~3 m, it represents one of the deepest and most hydrologically persistent water bodies within the Maple Flats complex (Buhlmann et al., 1999). As a closed-basin system, the pond is sustained by a combination of direct precipitation, surface runoff from the surrounding catchment, and groundwater seepage with no surface inlets or outlets. Closed-basin hydrology and continuous sedimentation create ideal conditions for preserving pollen, charcoal, and other paleoenvironmental proxies (Cohen, 2003).

Atmospheric conditions in the Shenandoah Valley at the base of the Blue Ridge in central Virginia are typical of a humid subtropical climate with hot/warm summers and mild/cool winters. The annual temperature is about 12–13°C with annual precipitation of about 900–1100 mm (Klopfer 1999). Rainfall is fairly evenly spread throughout the year, with increases in summer. In this region, droughts affect hydrology and vegetation dynamics periodically, while large-scale climate patterns such as the North Atlantic Oscillation and Atlantic Multidecadal Oscillation influence the interannual variability in moisture balance and fire patterns. These types of climatic patterns affect sedimentation rates and the ecological nature of ponds such as Maple Pond.

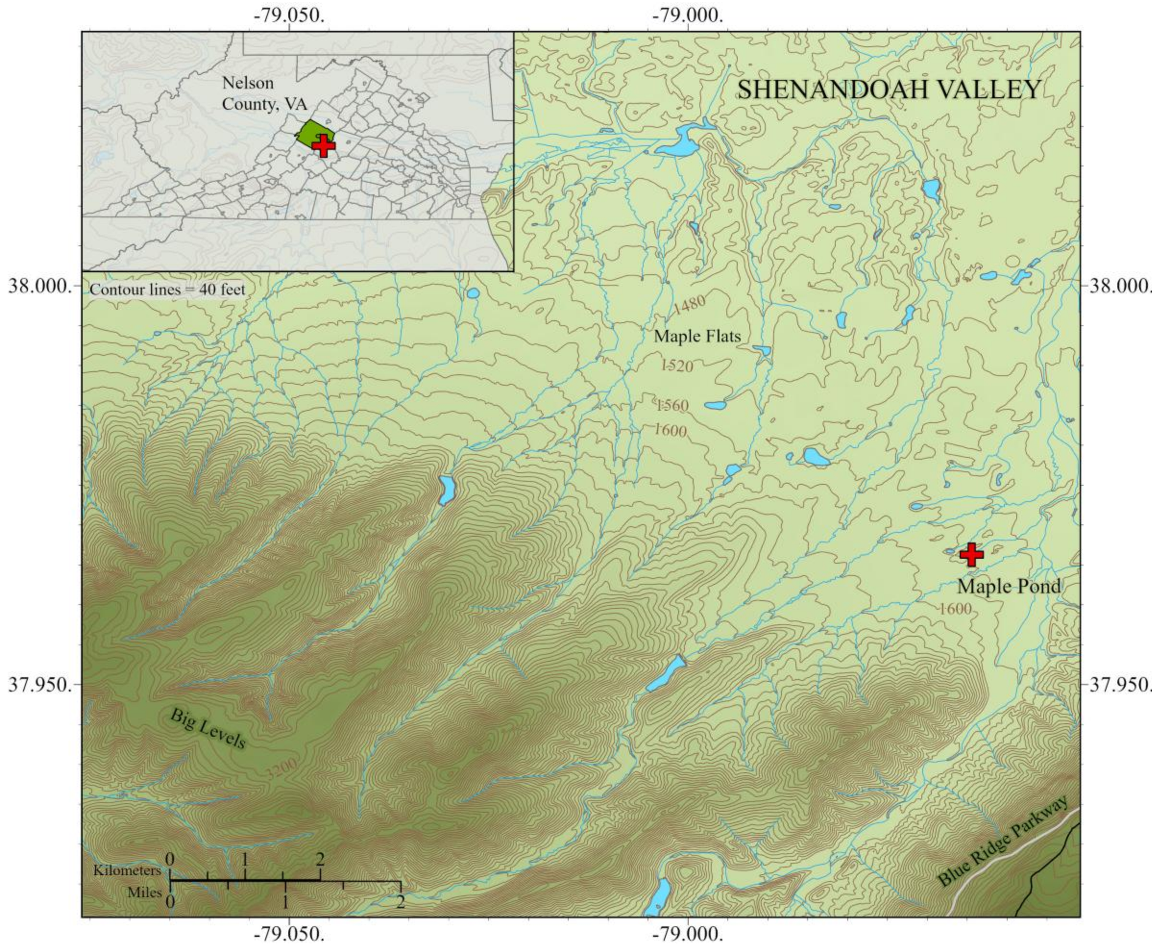

Figure 1. Location of Maple Pond situated in the Maple Flats Pond Complex, Augusta County, Shenandoah Valley, Virginia. The site lies at the base of the northwestern slope of the Big Levels plateau, Blue Ridge Mountains. Elevation is shown in feet (contours=40 ft intervals). Local hydrology includes several sinkhole ponds situated on karst terrain in the northeast portion of the map. The inset map illustrates the position of Maple Flats within the Commonwealth of Virginia (map created by K. Mullen).

Vegetation

The present-day vegetation cover in Maple Pond is composed of mixed oak-hickory-pine forests characteristic of central Appalachia. The Maple Flats uplands were described by Fleming and Van Alstine (1999) as dominated by chestnut oak (*Quercus montana*), white oak (*Q. alba*), and numerous hickory species (*Carya* spp.) with sparse distributions of pitch pine (*Pinus rigida*) and shortleaf pine (*P. echinata*). The forest understory contains mountain laurel (*Kalmia latifolia*), spicebush (*Lindera benzoin*), greenbrier (*Smilax* spp.), and several herbaceous species. Closer to the margins of the pond, the plant community changes to wetland assemblages including sedges (e.g., *Carex* spp.) and rushes (e.g., *Juncus* spp.), and emergent aquatic plants and small patches of seasonal submerged vegetation. These communities are very sensitive to changes in water-level and length of hydroperiod, returning organic material that is directly added to the sedimentary record of the pond.

Nutrient-poor, acidic soil and persistent moisture within the Maple Flats complex sustain rare and disjunct flora, including the federally endangered swamp pink (*Helonias bullata*) and the localized Virginia sneezeweed (*Helenium virginicum*) (Buhlmann et al., 1999). These species require damp open areas, which can be found in or around wetland basins of the complex. Patterns of vegetation in the area reflect soil fertility, canopy structure, hydrology, and disturbance history. This vegetation is a significant source of organic inputs to Maple Pond sediments.

Historical and Present Land Use

The Blue Ridge and Shenandoah Valley region supported Native American populations for millennia prior to European colonization (Delcourt & Delcourt, 1997). Palaeoecological evidence suggests that indigenous communities were present in the wider Appalachian region as early as 8000 BCE with a lasting ecological influence persisting for at least the last 4000 years (Delcourt & Delcourt, 1997). Throughout this period, indigenous people used fire as a tool for landscape management on a regular basis to drive game, clear understory vegetation, maintain open woodlands and meadows and generally improve wildlife habitat, and to promote fire-adapted oak and pine species (Pyne, 1982; Delcourt & Delcourt, 1997; Abrams & Nowacki, 2008). Palaeoecological research from the southern Blue Ridge has demonstrated a significant increase in the accumulation of charcoal in the last ~2,400 years, which is consistent with burning by humans that led to relatively open forests, with minimal erosion occurring before European contact (Leigh, 2016). These intentional burns produced a mosaic of woodlands, grassy patches and shrub openings on upland ridges and slopes, conditions that would have been characteristic of forests around the Maple Flats as well, as they are situated along the western slope of the Blue Ridge (Van Lear & Waldrop, 1989; Patterson, 2006). A regional fire history synthesis (Lafon et al., 2017) confirms that frequent, low intensity surface fires were common and spatially extensive in the Ridge and Valley and Blue Ridge Physiographic Provinces before European colonization and acknowledged the direct role of Native American burning in producing pyrogenic vegetation patterns (e.g., dominance by oak and pine that we observe today.

Agricultural practices intensified throughout eastern North America following the expansion of maize cultivation around 1000 CE (Smith, 1989). Flood plains and lower valleys were repeatedly cleared, and soils were disrupted (Peacock, 1998). Late Woodland (c. 900–1600 CE) societies expanded agricultural production during this time, and their activities contributed to localized increases of erosion and establishment of disturbance-tolerant vegetation (Peacock, 1998). Maple Flats, though not recognized as an agricultural hub, likely shares the same trends in cultivation and land alteration through its surrounding environment, the Shenandoah Valley, due to its rich bottomland and a long history of indigenous settlement. Such regional scale practices are useful to help explain the nature of disturbance regimes, and vegetation transitions that might have occurred in the Maple Pond catchment before the arrival of the Europeans.

In the 18th century, the Euro-American settlement resulted in a new type of land-use pressure in western Virginia including the Shenandoah Valley. Expansion of settlements into valleys and lower mountain slopes resulted in extensive forest clearing for row crops, pasture, building materials and open range grazing (Wilson, 2005; Yarnell, 1999). These activities became more rigorous in the 19th century, and repeated plowing and grazing caused an increase in soil erosion which in turn led to a significant loss of soil carbon for many Appalachian landscapes (Gragson & Bolstad 2006). Sediment records from the southern Blue Ridge indicate post-settlement rates of vertical accretion beginning in the late 1800s were approximately an order of magnitude faster than pre-settlement rates and were driven primarily by deforestation for the harvesting of timber, farming, and development (Leigh, 2016). Early settlers also used fire in land clearing and land management, but their burning regimes often differed from indigenous regimes in timing and extent of burning, which contributed largely to changes in woodland structure (Van Lear & Waldrop, 1989; Lafon et al., 2017). Similar dynamics probably occurred near the Maple Flats where forests around the pond may have been affected by the combined impacts of local clearing, grazing, and altered fire frequencies.

During the late 19th century and the beginning of the 20th century, industrial logging was a significant land use activity throughout the Blue Ridge Mountains and surrounding regions. Mechanized timber extraction cleared out extensive areas of mature oak-pine forests and created slash conditions which triggered extreme, stand replacing fires after harvests (Aldrich et al., 2014; Lafon et al., 2017). Dendrochronological studies from George Washington and Jefferson National Forests show frequent historical fires and a large reduction in fire activity after the early 1930s, which coincides with the establishment of the National Forest management (Clark, 2009). These intense post logging fires were a contrast to the frequent low intensity surface fires that had traditionally maintained open canopies and supported fire-adapted species (Brose et al., 2001). Tree-ring reconstructions from sites like Price Mountain in Virginia identified six major fire years between 1861 and 1925, followed by an end to fires associated with active fire suppression and cessation of pasture burning (Silver et al., 2013). The nearby Blue Ridge area was subjected to the same industrial timber activities, and the history of logging and fire disturbance likely impacted vegetation and fuel structure in the Maple Pond area.

During the 20th century, federal fire suppression policies led to a drastic decrease in the frequency and intensity of fires throughout the Appalachians. Dendroecological studies from the central Appalachians suggest that fire frequency was steady throughout the 18th and 19th centuries but decreased drastically in the early 20th century with the implementation of fire protection; burning stopped thereafter (Flatley et al. 2013; Lafon et. al. 2014). Fire exclusion enabled shade-tolerant, mesophytic hardwoods to increase and contributed to the ‘mesophication’ of fire-dependent forests (Abrams & Nowacki, 2008; Lafon et al., 2017). As fires became rare, oak and pine regeneration declined, understories became denser with fire sensitive species like maple and beech, and canopy closure increased across large portions of the region (Brose et al., 2001; Small & Chamberlain, 2015). Ecological mapping of the George Washington National Forest suggests that many forests within the region remain in early to mid-successional stages due to the long history of historical disturbances consisting of logging, agricultural clearing, and altered fire regimes from modern fire suppression (Simon, 2011). These combined histories, including indigenous burning, early agriculture, Euro-American settlement, industrial logging and current fire suppression, have collectively contributed to shaping the vegetation structure, fuel availability and disturbance regimes of the Shenandoah and blue ridge regions, including surrounding forests of the Maple Pond.

Modern Setting and Scientific Significance

The Maple Flats sinkhole pond complex is an ecologically unique landscape that has a higher biodiversity than that of the surrounding upland forests. Odonate surveys in the immediate vicinity documented 60 species of dragonflies and damselflies, representing nearly one-third of all species recorded in Virginia (Roble, 1999). Several of these taxa, including *Leucorrhinia glacialis* and *L. hudsonica,* are boreal species with disjunct populations in the Appalachians restricting their local distribution to permanent, acidic, fishless wetlands such as the Maple Flats ponds (Liberto & Studinski, 2021). For certain odonate species, the Maple Flats wetland serves as a geographically isolated refugium, hosting disjunct populations far isolated from their primary Coastal Plain distributions (Roble, 1999). Isolated populations of *Celithemis martha* and *Nehalennia* *integricollis* occur at Maple Flats, marking the extreme range limits for both species (Roble 1999). The variable hydroperiods, absence of predatory fish, and heterogeneous vegetation structure create diverse habitat niches that support the rich assemblage; consequently, the complex has been identified as a critical conservation priority for rare and specialized wetland fauna in Virginia (Fleming & Van Alstine, 1999; Roble 1999). Sinkhole ponds constitute critical habitat for amphibian communities within the region. Mitchell and Buhlmann (1999) document diverse amphibian assemblages within the Shenandoah Valley sinkhole pond system, including the state-endangered eastern tiger salamander (*Ambystoma tigrinum*), spotted salamanders (*Ambystoma maculatum*), and wood frogs (*Lithobates sylvaticus*). The fishes' character and seasonal inundation patterns of these wetlands provide essential breeding habitat for amphibians dependent upon predator-free environments for successful larval development. The presence of range-edge and habitat-specialist odonates at Maple Pond underscores the site's ecological uniqueness and suggests that the pond's sediment record may preserve evidence of past shifts in habitat suitability for these sensitive taxa.

Recent climate dynamics in the Shenandoah Valley and Blue Ridge region have further influenced the ecological setting of Maple Flats. Dendrochronological and sedimentary records indicate that interannual to decadal moisture variability is a defining characteristic of the central Appalachian climate, with drought events historically influencing fire frequency, forest cover, and wetland hydrology (Aldrich et al., 2014) At nearby Mountain Lake, Virginia, diatom assemblages and sedimentological evidence document episodic low-water intervals, revealing that decadal to centennial droughts have significantly lowered pond and lake levels in the region (Cawley et al., 2001). This hydrologic sensitivity suggests that the water balance and sedimentation regime of

Maple Pond are tightly coupled with regional precipitation patterns, positioning the site as a valuable repository of past hydroclimate variability. Multi-millennial sedimentary records from the southern Blue Ridge further demonstrate that erosion rates and charcoal deposition have varied considerably over time in response to climatic and land-use changes, providing long-term context for interpreting sedimentation processes at Maple Pond (Leigh, 2016).

The physical landscape of Maple Flats enhances its scientific value. Karst sinkhole wetlands are known to preserve long-duration sedimentary records due to their closed-basin hydrology, which facilitates uninterrupted deposition and minimizes erosional disturbances (Hettwer et al., 2003). Groundwater discharge from carbonate aquifers can stabilize water chemistry and provide a consistent moisture source, thereby enhancing organic matter preservation and promoting the formation of fen-like environments within certain sinkhole ponds (Hettwer et al., 2003). Because Maple Pond integrates inputs from adjacent slopes, local riparian vegetation, and surrounding forest communities, it functions as a sensitive recorder of environmental change across multiple spatial scales. The pond's location at the convergence of the Blue Ridge and Valley and Ridge physiographic provinces further increases its value for reconstructing regional environmental history.

The Appalachian region has extensive multi-proxy paleoenvironmental records that provide valuable context for interpreting sedimentary archives such as Maple Pond. Sediment cores from infilled sinkhole lakes have yielded detailed reconstructions of vegetation, climate, and sedimentation dynamics spanning thousands to millions of years (Shunk et al., 2009). Multi-proxy approaches combining pollen, charcoal, diatom, and geochemical analysis have successfully decoupled the effects of climate, fire, and human activity on past ecosystems in the Appalachians (Cawley et al., 2001; Hettwer et al., 2003). In the southern Appalachians, sedimentary charcoal records from wetlands and lakes provide critical evidence of changing fire regimes linked to both climatic variability and anthropogenic burning, offering a regional framework for interpreting fire history at sites such as Maple Pond (Delcourt & Delcourt, 1998; Leigh, 2016). The karst environment of Maple Flats, combined with its groundwater connectivity and closed-basin morphology, suggests that the Maple Pond sediments contain a continuous, high-resolution record suitable for a wide range of paleoenvironmental reconstruction.

Methods

Field Methods

A 147 cm sediment core was extracted from the central basin of Maple Pond in 2017 using a Russian peat borer following established protocols for wetland environments (Osborne et al., 2013). The Russian peat borer is specifically designed to minimize compaction and preserve stratigraphic integrity during extraction of organic-rich sediments in bogs and wetlands with water depths of under about 150 cm. The core was extracted from the deepest part of the pond (Figure 2), which was about 35 cm of water in September 2017 to aim for the most continuously accumulating part of the pond (Luo et al., 2023). Four overlapping drives, each retrieving 50 cm of sediment, were collected in succession, and each drive was advanced to depths overlapping with preceding intervals by 10 cm (Schnurrenberger et al., 2003). The overlap was intended to preserve stratigraphic continuity and reduce the potential for artificial compaction-related disturbance in the reconstructed record (Lisiecki et al., 2007). Upon extraction, each core was left on the borer "plate" and photographed immediately to preserve color, then logged to record positions of inclusions and color changes. The rounded side of the core shows stratigraphy and color much better in the field than after moving them to storage containers. Next, cores were placed in precut 50 cm-length PVC tubes (2.5 in diameter) split lengthwise to act as "cradles" for the sediment cores, which are semi-cylindrical. Lastly, cores were sealed with plastic wrap, aluminum foil, and duct tape to prevent desiccation and oxidation during transport and storage. Each was labeled with depth and sequence information. All sediment cores were transported to the Environmental Tracking Laboratory at

Virginia Tech the same day and stored at 4°C, a standard temperature for minimization of microbial activity, thus preservation (Dessoto, et al., 2025).

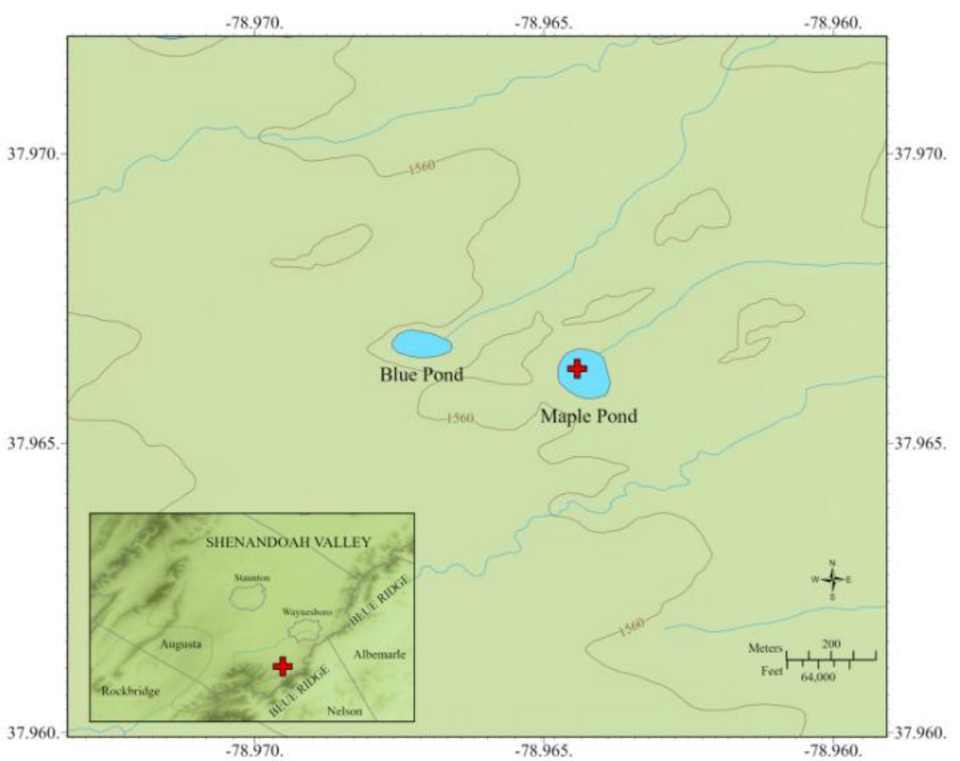

Figure 2: Local-scale map of Maple Pond and Blue Pond near the base of the Blue Ridge at approximately 478 m elevation in Augusta County, Virginia. The red cross symbol indicates the position where cores were extracted. Inset maps show nearby towns in the region.

Radiocarbon Analysis

Radiocarbon samples were submitted to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at the Woods Hole Oceanographic Institution for accelerator mass spectrometry analysis (McNichol et al., 1992). NOSAMS is one of the premier AMS radiocarbon dating facilities and follows standardized protocols for sample preparation and measurements (Xu et al., 2021). A total of seven AMS radiocarbon ages were successfully obtained (Table 1) across the depth interval of 28 to 131 cm. Six samples were macroscopic charcoal fragments; the sample at 70 cm yielded insufficient charcoal and was analyzed as bulk sediment organic carbon. The charcoal samples underwent acid-base-acid (ABA) pretreatment at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility to remove mobile organic phases (fulvic and humic acids) and inorganic carbon. The bulk sediment sample underwent standard acid pretreatment to eliminate inorganic carbon, following the same procedure described for preparing samples for carbon isotope analyses below (McNichol et al., 1992). NOSAMS provided measurements of Fraction Modern activity, conventional radiocarbon age in years before present (BP) with associated uncertainties (Stuiver and Polach 1977), measured or assumed $\delta^{13}C$ values used for isotopic fractionation correction (Stuiver and Polach 1977), and radiocarbon age with error. All radiocarbon conventional ages were calibrated to calendar years using IntCal20 calibration curve (Reimer et al 2020). IntCal20 is the most recent Northern Hemisphere atmosphere radiocarbon calibration curve and extends from 0 to 55,000 cal yr BP (Reimer et al. 2020). Individual radiocarbon ages were calibrated using OxCal version 4.4 (Bronk Ramsey 2009a).

Age-depth modeling was performed using Bchron in R (Haslett and Parnell, 2008). OxCal is a widely used program for radiocarbon calibration, and Bchron is a Bayesian chronology model that uses Markov Chain Monte Carlo (MCMC) sampling to estimate posterior probability distributions for sediment ages (Bronk Ramsey 2009a). Each dated sample was entered into the model as an R_Date object paired with its corresponding core depth in centimeters. Due to the core being retrieved using overlapping sequential drives (0-50 cm, 40-90 cm, 80-130 cm, and 98-148 cm), stratigraphic constraints were imposed during modeling to ensure respected depositional order and to eliminate stratigraphically imposed reversals (Blaauw and Christen 2011).

Overlapping core drives preserve stratigraphic continuity but require careful depth correlation to avoid duplication or omission of sediment intervals. A Bayesian Sequence model framework was applied to integrate the depth-constrained radiocarbon ages into coherent chronology. The sequence function in OxCal constrains dates to occur in stratigraphic order, with younger dates above older dates. The model was executed using default Markov Chain Monte Carlo (MCMC) settings. Posterior calibrated ages were exported for each dated depth, and an age-depth curve was constructed from the posterior probability distributions of calendar ages. Age estimates were interpolated at sediment depths sampled for analysis at 1 cm intervals using the depth-age function derived from the posterior model output. No smoothing functions or secondary Bayesian refinement in R or other statistical software was applied.

Loss-on-Ignition

Loss-on-Ignition (LOI) analysis of samples at contiguous 1 cm intervals quantified the water, organic matter, carbonate content, and “residue” (material remaining after combustion at 1000°C composed mainly of silica and iron oxides) of sediment samples Heiri et al., 2001). Wet sediment samples of 1 cm^3 volume were transferred into clean ceramic crucibles, pre-weighed to a precision of ±0.0001 g to ensure accurate mass determination (Heiri et al., 2001). The crucibles were placed in a drying oven at 100°C for 24 hours to remove pore water and establish a consistent dry mass baseline (Heiri et al., 2001), cooled and then weighed to determine water content. Next, samples were subjected to combustion in a muffle furnace at 550°C for a period of 2 hours to ensure complete oxidation of organic matter while minimizing the decomposition of carbonates (Santisteban et al., 2004; Heiri et al., 2001). After combustion, crucibles were allowed to cool in a moisture and dust-free dessicator cabinet. The crucibles were then weighed again to record organic matter loss (Heiri et al., 2001). To assess carbonate content, the crucibles were subsequently reheated in the muffle furnace at 1000°C for 1 hour. This high-temperature step facilitated the decomposition of carbonate content (Heiri et al., 2001). Quality assurance measures included verification of furnace temperatures using external thermocouple to ensure accurate and consistent heating (Ball 1964).

Charcoal Analyses

Macroscopic charcoal was sampled at 1 cm depth intervals except in places with insufficient material due to other analyses. Subsampled wet sediment was transferred into 15 mL centrifuge test tubes and immersed in a deflocculating solution of Decon 90 detergent and a 5% sodium hexametaphosphate solution for 24 hours; a treatment often used to help reduce clumping. Then samples were wet-sieved through a 250-µm mesh and thoroughly rinsed with deionized water to isolate macroscopic charcoal fragments suitable for subsequent analysis (Whitlock & Larsen, 2001). Charcoal fragments retained on the sieve were carefully transferred into a gridded petri dish containing deionized water. Quantification was conducted using a Leica S6D Stereo Zoom microscope at magnifications ranging from 6x to 40x. Stereomicroscopes in this magnification range are standard equipment for macroscopic charcoal analysis and allow for accurate identification of charcoal morphology and distinction from other dark-colored particles (Whitlock

& Larsen, 2001). Charcoal particles were differentiated from other dark particles by their black opaque coloration, glass-like shine under a light, general angularity, pattern of fracture when probed, and sometimes evident plant tissue microstructures. The number of charcoal fragments and the presence of sphagnum in each sample were then recorded along with notes on morphological attributes of charcoal fragments. Qualitative observations such as sediment color, clumping when present, and presence of plant fibers, faunal remains, or clay were also recorded. Charcoal abundance was standardized to fragments per cubic centimeter (fragments cm^{-3}) of sediment to facilitate comparison across depth intervals (Whitlock and Millspaugh 1996).

Carbon Isotope Analyses

Stable carbon isotope measurements were obtained at 1 cm depth intervals across the entire core to characterize organic matter sources and paleoenvironmental conditions (Meyers and Lallier-Verges 1999). Clean 15 mL centrifuge tubes were labeled sequentially (MPA 01, through MPA 147) with the mass of each empty, uncapped tube recorded using a calibrated laboratory balance. Approximately 0.2 g of air-dried sediment was added to each tube, and the loaded tube was reweighed to record exact sample mass. Carbonates were removed by acidification with 2M hydrochloric acid (HCl, ~4 mL per tube) (Könitzer et al., 2012). HCl treatment is a necessary process carried out to ensure the removal of inorganic carbon and isolate the organic carbon fraction for accurate $\delta^{13}C$ analysis (Brodie et al., 2011). The solution was introduced into the samples using a pipette and the tubes vortexed as needed to expose unreacted grains and properly mix sediment with acid liquid. After this process, tube caps were left loosely resting to allow safe venting of CO_2 generated during the acid-carbonate reaction (Harris et al., 2001). The reaction was allowed to proceed for at least 24 hours before rinsing steps to ensure complete carbonate removal in accordance with established protocols (Könitzer et al., 2012; Galy et al., 2007). The acidified sediment was rinsed iteratively with deionized water to remove residual acid and liberate carbon dioxide. Each rinse cycle involved centrifuging for 5 minutes at 4000 rpm, and careful supernatant decantation. This process was repeated a minimum of four times until the final rinse achieved neutral pH (Harris et al., 2001). After neutralization, uncapped tubes were placed upright in a drying oven maintained at 55°C until all residual water had evaporated, and the sediment formed dry, friable cakes. Tubes were then removed, allowed to cool and reweighed to document the mass of dried, decarbonated sediment. Dried samples were transferred in small portions to an agate mortar and pestle and gently ground to fine, homogeneous powder. The mortar and pestle were thoroughly wiped with ethanol between samples to minimize cross-contamination.

Homogenized powders were sorted into respective labeled tubes ready for combustion analysis. Dried powders were incrementally transferred into tin capsules (Elemental Microanalysis, D1002), handled with stainless-steel forceps to prevent contamination and were weighed to attain a mass of approximately 0.4-4 mg using a microbalance. Each capsule was subsequently folded and tightly crimped into a compact pellet, a step crucial for ensuring complete and efficient combustion during subsequent EA-IRMS analysis. All sample masses were recorded on laboratory weigh sheets for traceability, and procedural blanks were included as controls to monitor potential contamination. Three standards (IAEA CH6, IAEA CH7, and EA Microanalysis Wheat flour), were encapsulated and interspersed throughout the run. This approach aligns with standard practices for high-precision EA-IRMS analysis, where the regular inclusion of standards and blanks are essential for calibration and quality assurance (Szpak et al. 2017). Isotopic measurements were performed using a Vario isotope cube elemental analyzer interfaced with an Isoprime 100 isotope-ratio-monitoring mass spectrometer in the Stable Isotope Laboratory in the Department of Geosciences at Virginia Tech. The elemental analyzer determined total organic carbon (%C) and total nitrogen (%N) concentrations concurrently with stable carbon isotope ratios. Values for $\delta^{13}C$ were normalized to Vienna Pee Dee Belemnite (VPDB) scale via two-point linear normalization using international reference materials IAEA CH6 (accepted $\delta^{13}C$ = -10.449‰) and IAEA CH7 (accepted $\delta^{13}C$ = 32.151‰). EA Microanalysis Wheat Flour (accepted $\delta^{13}C$ = 27.21‰) served as an additional quality control standard. Analytical precision, calculated from replicate analysis of standards, was ± 0.2‰ for $\delta^{13}C$ (1σ).

Results

Sediment core description

The 147-cm sediment core retrieved from Maple Pond, Virginia exhibits stratigraphic characteristics typical of organic-rich wetland systems across eastern North America (Gorham, 1991). The uppermost sediment (0-12 cm) has dark coloration (Munsell color 10YR 2/1), with a mushy, poorly consolidated texture reflecting high organic matter content and minimal mineral fraction. This surface layer consists predominantly of fibrous plant material lacking visible silt or sand grains, consistent with modern peat-accumulating wetland environments where terrestrial vegetation provides the primary sediment source. From 12-20 cm depth, sediments retain the characteristic of very dark brown coloration (10YR 2/2) of organic-rich deposits but exhibit slightly greater structural integrity than overlaying material. A gradual color transition occurs between 20-40 cm, with sediments becoming progressively lighter while maintaining elevated organic content, a pattern observed in numerous Holocene wetland sequences from the Appalachian region (Kneller & Peteet 1999). The interval from 40-47 cm shows the lightest coloration observed in the core (dark grayish brown, 10YR 4/2), potentially reflecting reduced organic accumulation or enhanced mineral input during this depositional period. Below 47 cm, sediments display variations in Munsell color and textures that were predominantly clay but with layers of silt/sand and ending in coarser material in the basal sediments.

Notable features observed during core description included a small rock fragment at 17 cm depth and a larger pebble at 40 cm, potentially indicating episodic mineral input from watershed runoff. Plant fiber density varied substantially throughout the core, with maximum fiber concentration and length observed near the surface at 10 and 17 cm depth. Visual examination in the laboratory identified charcoal-rich intervals at 33-38 cm and 46-49 cm.

Radiocarbon Dates and Age-Depth Model

Seven radiocarbon dates were obtained from the Maple Pond core, providing chronological control across depths from 28 to 131 cm (Table 1). One date from 48 cm depth exhibited evidence of potential laboratory contamination and was subsequently excluded from chronological modeling. The remaining six dates were used to build the age-depth model. The basal radiocarbon date at 131 cm (of a 147 cm core) yielded an age of 12, 700 ± 65 ^{14}C yr BP, calibrating to a median age of 15,048 cal yr BP (15,335-14,945 cal yr BP at 2σ confidence), indicating that sediment accumulation at this site initiated during the Late Pleistocene, more than 15,000 years ago. The shallowest dated horizon at 28 cm produced an age of 2,280 ± 15 ^{14}C yr BP (median 2,306 cal yr BP; 2,345-2,181 cal yr BP at 2σ), documenting continued sediment accumulation through the late Holocene.

Table 1: Radiocarbon dates (^{14}C yr BP) and calibrated ages (2σ) for Maple Pond (MPA) sediment core, calibrated using OxCal 4.4 and IntCal20. The date at 48 cm was excluded from the age model due to suspected laboratory error. The date at 81 cm exhibits a stratigraphic age reversal relative to the underlying sample at 103 cm, likely reflecting incorporation of reworked charcoal.

Lab No.	**Depth (cm)**	**Material dated**	**^{14}C yr BP ± (yr)**	**2σ Calibrated yr BP**	**Median Calibrated Age (cal yr BP)**	**Probability (%)**
OS-187480	28	Charcoal	2280 ± 15	2345–2181	2306	73.1; 22.3
OS-186988	*48*	*Charcoal*	*9640 ± 40*	*11188–10784*	*11188*	*42.0; 5.8; 47.7*
OS-187338	70	Sediment Organic Carbon	7710 ± 25	8546–8418	8546	95.4
OS-187482	81	Charcoal	10250 ± 40	12429–11760	11833	2.0; 0.4; 0.6; 91.3; 1.0
OS-187481	103	Charcoal	9640 ± 40	11188–10784	11188	42.0; 5.8; 47.7
OS-176725	120	Charcoal	10300 ± 55	12464–11830	12464	17.2; 4.4; 6.1; 67.6
OS-165400	131	Charcoal	12700 ± 65	15335–14945	15048	95.4

**Excluded from age model due to suspected laboratory handling error given the identical result on the 103 cm sample).*

Age depth modeling using Bchron with the IntCal20 calibration curve revealed one stratigraphic age reversal within the sequence. The charcoal-based determination from81cm (10,250 ± 40 ^{14}C yr BP; median 11,833 cal yr BP) yielded an anomalously old age relative to the underlying determination from 103 cm (9,640 ± 40 ^{14}C yr BP; median 11,188 cal yr BP), creating a stratigraphic inversion wherein a shallower sample yielded a comparatively older age than anticipated based on the contextual chronological framework. The remaining five radiocarbon dates exhibited stratigraphic consistency and were used to construct the age-depth relationship for interpolation of ages at undated depths (Blaauw & Christen, 2011). Sediment accumulation rates varied throughout the sequence, with slower accumulation during the late Pleistocene (120-131 cm) and in the early to mid-Holocene (28-70 cm), compared to relatively rapid accumulation during the Pleistocene-Holocene transition (deglaciation, 70-120 cm). Extrapolating the sedimentation rate between the bottom two median dates (12,464 cal yr BP at 120 cm and 15,048 cal yr BP at 131 cm; each cm = about 235 yrs) downcore to the undated bottom section (131-147 cm) would add 3,760 cal yr BP suggesting that the total time period represented by this core is over 18,000 years.

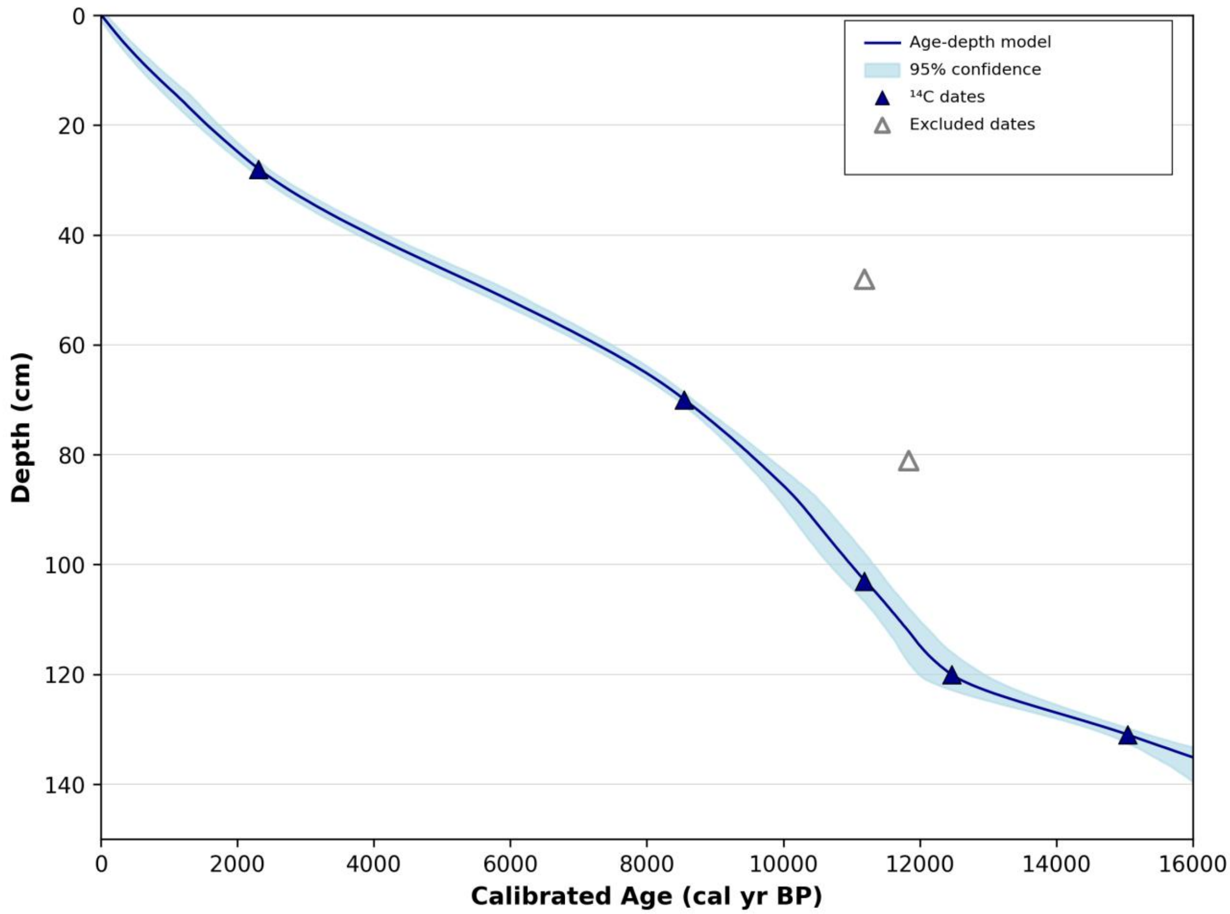

Figure 3: Age-depth model for the Maple Pond sediment core showing calibrated radiocarbon dates (triangle with 2 σ uncertainty ranges) and modeled age-depth relationship (line with 95% confidence envelope). The date at 48 cm was excluded from the model due to suspected laboratory error. The date at 81 cm represents an age reversal likely reflecting reworked charcoal.

Loss-on-Ignition

Loss-on-ignition analysis (1 cm resolution) of the 147 cm core revealed substantial down-core variation in sediment composition, reflecting changes in organic matter production, preservation, and mineral input over the past 15,000+ years (Figure 4). Organic matter content, estimated from mass loss at 550°C, ranged from approximately 10% to 40% of dry sediment mass. The highest organic concentrations (35-40%) occurred in the upper 40 cm of the core, documenting modern and recent organic-rich wetland conditions similar to those observed at other sinkhole ponds in the

Maple Flats region. These elevated organic values reflect periods of enhanced wetland productivity and favorable preservation conditions during the late Holocene (Booth, et al., 2016).
Organic content decreased progressively with depth, averaging 20-30% between 40 and 90 cm in depth, and declining further to 10-20 % in the deepest sediments (90-147cm), which contained higher sand component grading downward. This down-core trend from high surface organic to lower basal value is characteristic of lake and pond sediment cores, where upper sediments receive fresh input of aquatic plants and animals while deeper sediments experience greater decomposition and compaction, resulting in increased mineral content with depth.

The residual fraction, consisting primarily of mineral silicates and any other refractory materials remaining after combustion at 1000°C, exhibited an inverse relationship with organic matter content. Silicate abundance ranged from approximately 55-70% in organic rich surface sediments as high as 85-95% in deeper, mineral-rich intervals. The increase in mineral content with depth corresponds with the decline in organic content observed throughout the lower core section.

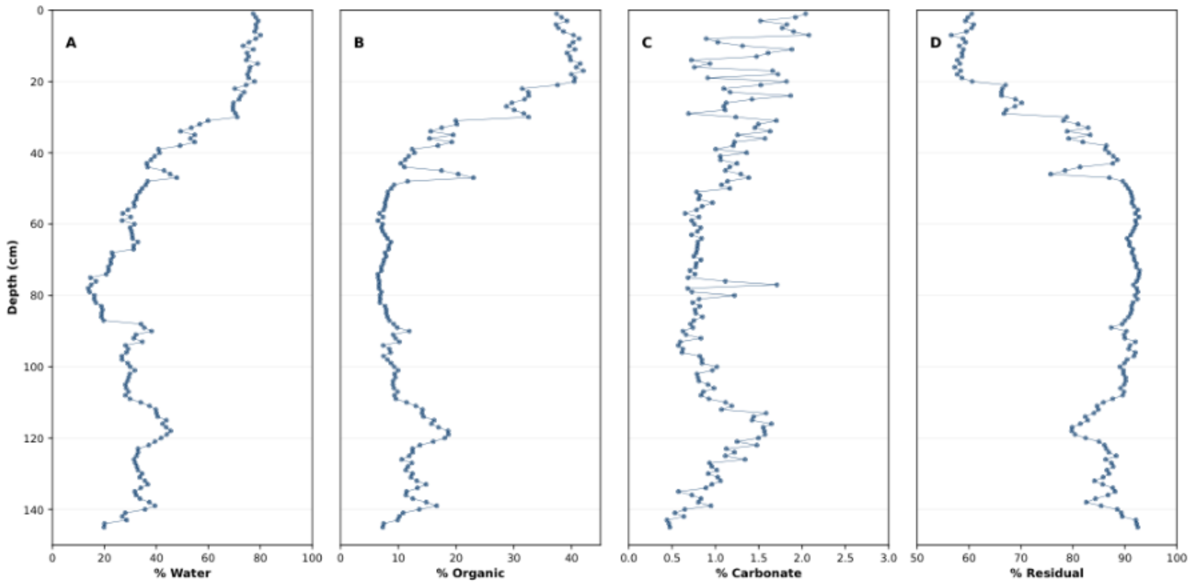

Figure 4: Loss-on-ignition results showing down-core variation in water content (%), organic matter content (%), carbonate content (%), and residual mineral fraction (%) plotted against depth (cm) for the Maple Pond core. Data represents 1cm sampling intervals.

Charcoal Analysis

Macroscopic charcoal concentrations throughout the Maple Pond core revealed substantial variability, ranging from background levels of 0-10 fragments/cm^3 to peak concentrations exceeding 400 fragments/cm3 (Figure 5, Panel C). Large charcoal particles (>100 µm) preserved in lake and wetland sediments provide a proxy record of fire activity within approximately 10-100 km of the depositional site, with local fires (<10 km) exerting disproportionate influence on charcoal accumulation compared to more distant sources (Mooney & Tinner, 2011). The charcoal record from Maple Pond documents substantial temporal variability in local fire regime over the past approximately 15,000 years, revealing intervals of both elevated and suppressed biomass burning (Vachula et al., 2024).

Stratigraphic charcoal distribution (vs. depth)

Charcoal-rich intervals were visually identified during core examination at 120-129 cm depth and 40-49 cm, with the most prominent peak occurring at approximately 40-49 cm depth (Figure 4, Panel C). Raw charcoal counts from these intervals revealed maximum concentrations, reaching 434 fragments/cm^3 at 48 cm depth and sustained elevated values throughout the 40-49 cm interval. Background charcoal concentrations, defined as sustained intervals with fewer than 50 fragments/cm^3, characterized much of the sediment record, particularly in the upper 35 cm and lower 60cm of the core. These low background values align with the infrequent, low-intensity fire regimes characteristic of mesic eastern deciduous forests (Stambaugh et al., 2015), although fire frequency may have risen during intervals of intensified indigenous land use the last 4,000 years (Nowacki & Abrams, 2008).

Stable Carbon Isotope Values and Elemental Compositions

Stable carbon isotope values ($\delta^{13}C$) and elemental composition (%C, %N, C:N ratios) measured at 1 cm intervals throughout the 147 cm core characterize organic matter sources and provide insights into paleoenvironmental conditions over the past 15,000 years (Figure 5A&B). $\delta^{13}C$ values ranged from approximately -29‰ to -27‰ (VPDB), with the lowest values occurring in the deepest, oldest sediments and higher values toward the surface. Below ~100 cm, $\delta^{13}C$ values remain consistently low (-29‰ to -28‰). A gradual increase occurs between 100 cm and 70 cm, reaching -27‰ to –27.5‰ in the upper 40 cm. Atomic C:N ratios vary from approximately 10 to over 35, with maximum values in sediments below 100 cm. The lower portion of the core (100-147 cm) exhibits C:N ratios of 25-35 and is mostly within the C:N "terrestrial" shaded zone (red/pink, Figure 5B), consistent with nitrogen-poor vascular plant material (Zeh et al., 2020). Between 50 and 100 cm, intermediate ratios (18-25) indicate mixed organic sources. Above 50 cm, values decline to 10-18, shifting toward the aquatic field (blue shaded zone), reflecting increased nitrogen-rich aquatic and wetland contributions. C:N ratios below 10 indicate algal or aquatic plant dominance, 10-20 reflect mixed aquatic-terrestrial sources, and >20 indicate nitrogen-poor vascular plants rich in cellulose and lignin (Meyers, 1994).

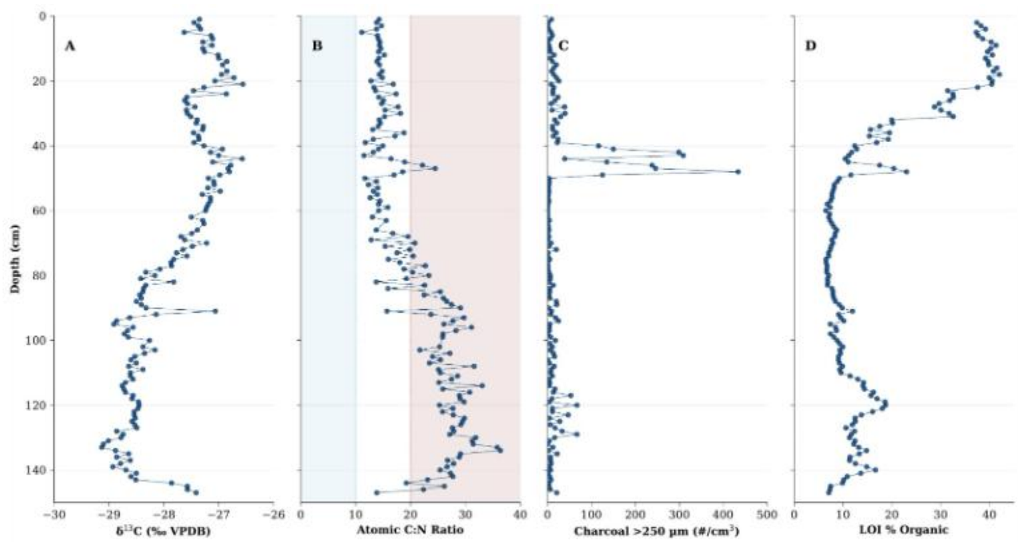

Figure 5: Multi-proxy stratigraphic figure for the Maple Pond sediment core showing (A) stable carbon isotope values ($\delta^{13}C$, ‰VPDB), (B) atomic C:N ratios, (C) macroscopic charcoal concentration (fragments >250 μm/cm^3), and (D) loss-on-ignition organic matter content (%) plotted against depth (cm).

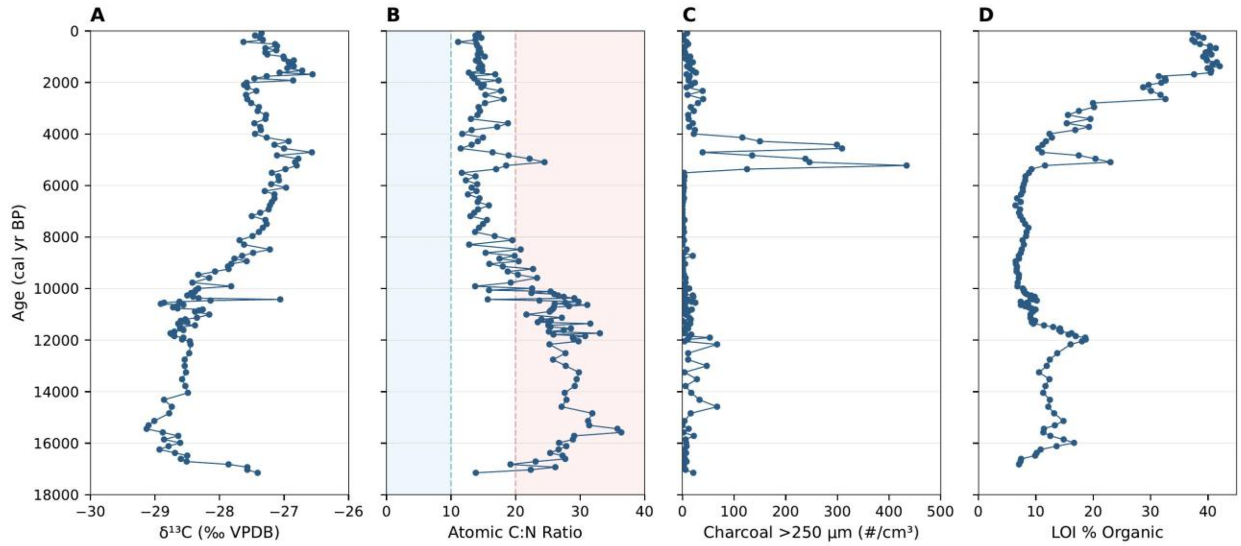

Figure 6: Multi-proxy figure for the Maple Pond sediment core showing (A) stable carbon isotope values (δ13C, ‰VPDB), (B) atomic C:N ratios, (C) macroscopic charcoal concentration (fragments >250 µm/cm3), and (D) loss-on-ignition organic matter content (%) plotted against interpolated age (cal yr BP). All proxies are plotted on a common age scale derived from the age-depth model.

Total organic carbon content ranged from approximately 2% in basal sediments to 25-28% in the uppermost core (Figure 7A), with values increasing progressively toward the surface, generally tracking loss-on-ignition organic matter estimates and confirming the increasingly organic-rich character of Maple Pond sediments through the Holocene. Total nitrogen content ranged from approximately 0.1% in deep sediments to 2.0-2.5% in the uppermost samples (Figure 7B), resulting in atomic C:N ratios spanning from approximately 10 to 38 (Figure 5B; Figure 6B).

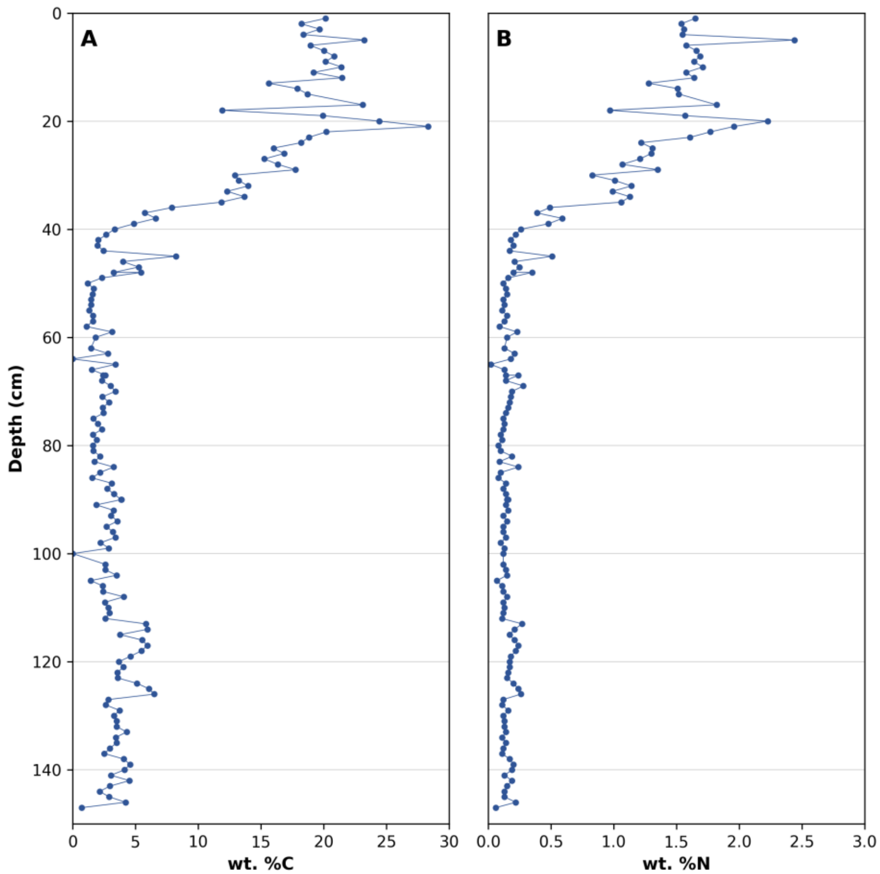

Figure 7: Total organic carbon content (wt. %C, Panel A) and total nitrogen content (wt. %N, Panel B) plotted against depth (cm) for the Maple Pond sediment core. Both parameters increase progressively toward the surface, reflecting enhanced organic and nutrient accumulation during the late Holocene, with %C reaching 25-28% and %N reaching 2.9-2.5% in the uppermost sediments.

Biplot Analysis

The C:N and $\delta^{13}C$ biplot (Figure 8) reveals systematic temporal changes in organic matter composition across the Maple Pond sediment record. Zones are demarcated by established reference fields: lacustrine algae (C:N <10) and terrestrial C_3 land plants (C:N >20), with intermediate values (C:N 10-20) indicating mixed organic matter sources (Meyers & Ishiwatari 1993). Late Glacial sample (>14 ka; orange points) cluster within the terrestrial C_3 plant field, reflecting elevated C:N ratios (18-37) and low $\delta^{13}C$ values (-28‰ to -29‰), consistent with dominance of nitrogen-poor vascular plant material (Meyers 1994; Lamb et al., 2006). The deglaciation-phase (14-11 ka; red points) reveals a more dispersed distribution pattern, with the majority of the points remaining within the terrestrial field yet extending toward intermediate C:N values (23-33), suggesting continued terrestrial dominance during this transitional interval. Early-Mid Holocene (11-4 ka; light blue points) are distributed throughout the terrestrial and mixed source fields, with C:N ratios of 12-31 and $\delta^{13}C$ values between –27‰ and -29‰, signifying episodic elevation of aquatic and emergent wetland productivity concurrent with warmer Holocene conditions (Shuman & Donnelly 2006). Late Holocene samples (<4 ka; dark blue points) congregate predominantly in the lacustrine algae and mixed-source zones, with notably reduced C:N ratios (11-19) reflecting intensified contributions from nitrogen-enriched wetland flora and aquatic organic matter (Meyers & Teranes 2001). The progressive migration of samples from the terrestrial field at the base of the core toward lower C:N values through time document a long-term transition in organic matter provenance, from woody terrestrial-dominated inputs during the Late Pleistocene to progressively wetland-influenced sources during the late Holocene, consistent with accumulated peat and wetland expansion (Gorham 1991).

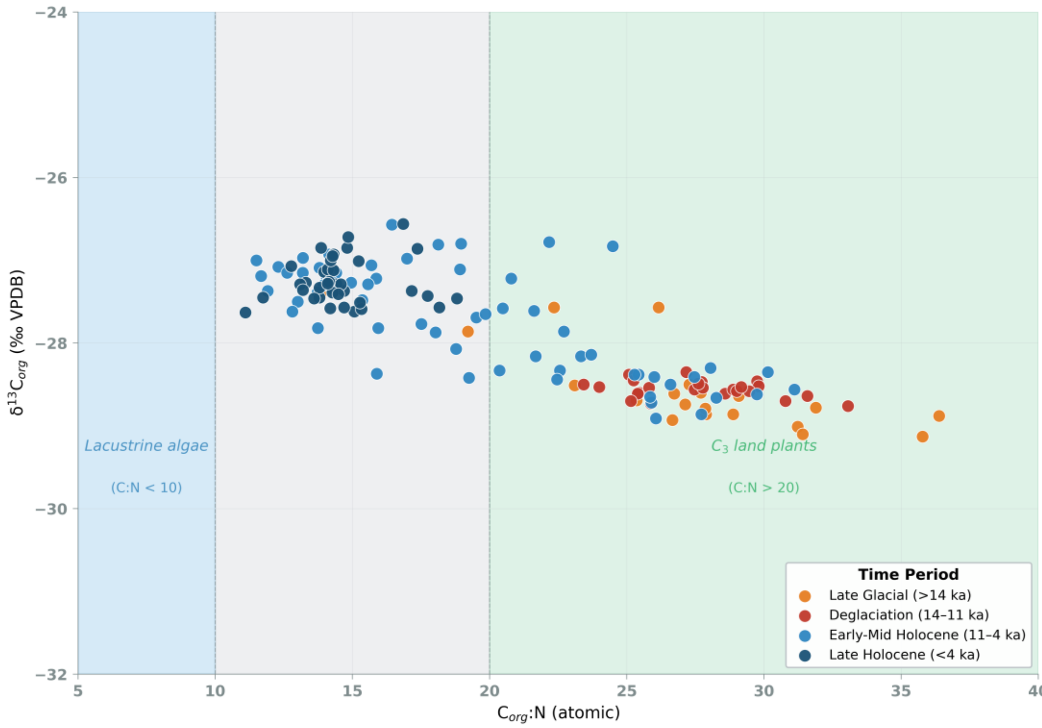

Figure 8: Biplot of stable carbon isotope values ($\delta^{13}C$, ‰VPDB) versus atomic C:N ratios from Maple Pond sediments, color-coded by time period. Reference fields indicate diagnostic ranges for lacustrine algae (C:N <10, left shaded region) and terrestrial C_3 plants (C:N >20, right shaded region). Data show temporal progression from terrestrial sources in the Late Glacial and Deglaciation intervals (orange and red points in upper right) through mixed sources during early-mid Holocene (teal points scattered between fields), to continued terrestrial dominance in the Late Holocene (dark blue points in lower right).

Discussion

The Maple Pond multi-proxy sequence records a continuous sedimentary archive spanning approximately 18,000 years, extending from the Late Pleistocene through the Holocene. The integration of loss-on-ignition, charcoal, and stable isotope datasets provides a comprehensive paleoenvironmental reconstruction that documents temporal variability in vegetation composition, fire regimes, and sediment provenance that reflects broader environmental transformations across this climatically dynamic interval. We compared the stratigraphic trends in organic matter content, microcharcoal abundance, C:N ratios, and $\delta^{13}C$ values to paleoenvironmental archives from other central Appalachian sites, including Cranberry Glades (Watts, 1979), Browns Pond (Kneller & Peteet, 1993, 1999), and neighboring ponds in the Maple Flats complex, Spring Pond (Craig, 1969; formerly named Hack Pond (Buhlmann et al., 1999), and Twin Pond, Vachula et al., (2024).

Late Pleistocene Environment (≥15,000-11,700 cal yr BP)

The lowest radiocarbon date at 131 cm depth in the Maple Pond core yielded a median calibrated age of approximately 15,048 cal yr BP, positioning the Maple Pond sediment record as representative of the late-glacial interval. Extrapolating of sedimentation rates from the 120 and 131 cm section suggests that the lowest 16 cm of undated sediment (131-147 cm) may represent 15,000-18,000 cal yr BP. This basal age demonstrates broad correspondence with the initiation of organic sedimentation at Browns Pond, Virginia, approximately 50 km northeast of Maple Pond, at about 20,700 ^{14}C yr BP (calibrated from 17,130 ^{14}C yrs reported in Kneller & Peteet, 1993). Spring Pond, about 3.5 km northwest of Maple Pond within the Maple Flats complex was dated to around 20,000 cal yr BP (Lynch & Clark 2002). Twin just Pond, just a few steps south of Spring

Pond, preserves an approximately 27,000-year record (Vachula et al., 2024), making it one of the oldest continuous sedimentary archives in the central Appalachian region.

During the Late Pleistocene period (>15,000-11,700 cal yr BP), the local area around Maple Pond may have experienced lower levels of fire compared to later time periods as represented by minimal macrocharcoal concentrations (<10 fragments/cm^3). Low organic content (~10% LOI), consistently depleted $\delta^{13}C$ values (-28‰ to -29‰), and elevated C:N ratios (25-30) indicate that organic matter in Maple Pond derived predominantly from woody, nitrogen-depleted C_3 vegetation, while aquatic algae and phytoplankton typically exhibit C:N ratios below 10 due to their protein-enriched, cellulose-depleted composition (Meyers, 1994). The elevated C:N ratios specifically suggest lignin-rich material characteristics of vascular land plants. Pollen records from Browns Pond document the presence of a closed boreal forest of *Pinus-Picea-Abies* occupying the region during this interval (Kneller & Peteet, 1993). Comparable late-glacial boreal forest compositions are documented by the pollen record at nearby Spring Pond (formerly Hack Pond), where Craig (1969) recorded vegetation dominated by spruce forests with white pine constituents. On the Allegheny Plateau to the northwest, pollen sequences from Cranberry Glades, West Virginia, document analogous *Pinus-Picea* assemblages during the late-glacial period (Watts, 1979).

At Twin Pond, Vachula et al., (2024) documented three discrete periods of fire activity spanning the glacial-interglacial transition: minimal fire activity during the glacial period (27,000-17,700 cal yr BP) characterized by wood and needle fuel morphotypes; elevated fire activity during deglaciation (17,700-11,000 cal yr BP); and attenuated fire activity throughout the Holocene (11,000 cal yr BP to present). Notably, fire activity at Twin Pond increased markedly during the deglaciation in the absence of broad vegetation compositional changes, suggesting that temperature and precipitation variability functioned as the primary drivers of fire activity during this interval, rather than fuel availability or type (Vachula et al., 2024). The minimal charcoal concentrations observed in the Late Pleistocene sediments at Maple Pond are consistent with this regional pattern of suppressed glacial-period fire activity.

Early-to-Mid-Holocene Transition (11,700-6,000 cal yr BP)

During the early-to-mid Holocene (11,700-6,000 cal yr BP), the local area around Maple Pond experienced significant environmental transformation, transitioning from a terrestrially-dominated system to one with increasing aquatic productivity, as represented by the shift toward less depleted $\delta^{13}C$ values (-29‰ to -27‰) and decreasing C:N ratios (25-30 to 12-25). The early-to-mid Holocene represents the most environmentally dynamic interval in the Maple Pond record. Biplot analysis (Figure 8) reveals that while the majority of samples from this period cluster within the terrestrial-dominated range (C:N > 20), a subset extends toward lower C:N values within the mixed-source zone (C:N 10-20), indicating episodic increases in aquatic productivity concurrent with warmer climatic conditions and stabilizing vegetation assemblages. The shift toward intermediate C:N values (12-25) between approximately 70 and 100 cm depth suggests transitional organic matter sources as the ecosystem adjusted to Holocene climatic conditions.

Elevated temperatures enhance aquatic productivity through multiple interconnected physiological and biogeochemical mechanisms. Phytoplankton growth rates and corresponding nutrient assimilation generally increase with rising temperature (Reynolds, 2006), while warming accelerates nutrient mineralization and internal cycling processes within lacustrine systems (Farrell et al., 2020). Additionally, prolonged ice-free intervals and extended growing seasons associated with warmer climatic regimes promote intensified primary production in temperate lacustrine environments (O'Beirne et al., 2017). The progressive increase in $\delta^{13}C$ values through this interval, from approximately -29‰ at the base to -27‰ in mid-Holocene sediments, likely reflects this enhanced lacustrine productivity and increasing contributions from aquatic organic matter sources, rather than an expansion of C_4 grasses, which were less prevalent in the Central Appalachian region during this period due to cooler temperatures and closed forest canopy conditions (Teeri & Stowe, 1976; Edwards et al., 2010).

Pollen records from regional sites document the transition from boreal to deciduous forests during this interval. At Spring Pond, Craig (1969) recorded the replacement of spruce forests by oak and hardwood taxa during the early Holocene. At Browns Pond, Kneller & Peteet (1993) observed that *Abies* pollen occurred in greater abundance from 16,000 to approximately 9,000 BP relative to neighboring localities, indicating spatial heterogeneity in the compositional structure of the late-glacial boreal forest across the central Appalachian region. The transition from conifer to hardwood dominance occurred between approximately 12,000 and 10,000 cal yr BP at these sites, broadly coincident with the period of maximum environmental instability recorded in the Maple Pond geochemical proxies.

Fire History and Regional Comparisons

The charcoal maximum observed at 40-49 cm depth constitutes a prominent feature of the Maple Pond record that warrants comparison with the regional fire histories. Based on the age-depth model, this charcoal peak corresponds to approximately 5,000-6,000 cal yr BP, positioning it within the mid-Holocene. A secondary, minor charcoal peak occurs between 120 and 130 cm depth, corresponding to approximately 12,000-14,000 cal yr BP during the late-glacial to early Holocene transition.

The macroscopic charcoal fraction (>250 μm) analyzed at Maple Pond provides information regarding local fire history, as larger charcoal fragments are deposited relatively close to their source. Research on charcoal dispersal indicates that macroscopic charcoal particles generally record fire activity within approximately 10-50 km of a depositional site, with proximal fires exerting disproportionate influence on charcoal accumulation (Peters & Higuera, 2007; Vachula et al., 2018). Vachula et al., (2018) demonstrates that the source area for >250 μm charcoal particles is within approximately 25 km of a lacustrine basin, whereas particles in the 63-150 μm size range may undergo transport over considerably greater distances. Generally, macrocharcoal represents the local watershed of a wetland, pond, or lake being deposited by streams and erosion of nearby slopes.

The mid-Holocene charcoal maximum at Maple Pond coincides with evidence for warmer and drier conditions documented at regional sites, Tanner et al. (2015) presented multi-proxy evidence from a wetland deposit in the southern Appalachian Mountains of North Carolina documenting warm, dry conditions during the mid-Holocene between approximately 7,000 and 5,000 cal yr BP, coinciding with the Hypsithermal interval documented elsewhere in North America (Wanner et al., 2008). Their carbon isotope data showed higher $\delta^{13}C$ values during this interval, interpreted as reflecting increased contributions from C_4 grasses under warmer and drier conditions. At Browns

Pond, Kneller and Peteet (1999) reported evidence of depressed water levels during the early Holocene, approximately concurrent with the expansion of *Quercus spp*. (oak).The mid-Holocene charcoal peak at Maple Pond may therefore reflect increased regional fire activity associated with warmer and drier conditions during the mid-Holocene warm period, the Hypsithermal, which would have enhanced landscape flammability.

At Twin Pond, Vachula et al. (2024) found that during the Holocene, charcoal accumulation rates broadly corresponded with the relative abundance of conifer taxa and charcoal morphotypes characteristic of needle fuels, suggesting that fire-vegetation relationships became more pronounced during the Holocene. They documented a shift in charcoal morphotypes from wood and needle types characteristic of the glacial and deglacial periods to deciduous leaf, herbaceous material, twig, and rootlet morphotypes during the Holocene, reflecting the regional transition to deciduous forest vegetation. Notably, Vachula et al. (2024) observed that the increase in hardwood taxa at approximately 10,000 cal yr BP was associated with a decline in fire activity at Twin Pond, contrasting with patterns observed at other eastern North American sites where hardwood expansion coincides with increased fire frequency.

The divergence in the timing of charcoal peaks between the Maple Pond, Spring Pond, and Twin Pond records with Maple Pond showing maximum charcoal concentrations during the mid-Holocene (~5,000-6,000 cal yr BP) while Twin Pond recorded peak charcoal accumulation during the deglaciation (17,700-11,100 cal yr BP) despite their geographic proximity (~3 km separation), necessitates an evaluation of local-scale controls governing charcoal deposition. Lynch and Clark (2002) emphasized that local variables, including fuel loading, topography, and microclimatic conditions, frequently exert more pronounced influence on fire records than regional climatic patterns, potentially explaining why nearby basins can preserve substantially distinct charcoal histories. Lynch and Clark (2002) also interpreted very low accumulation of charcoal in sediments from Spring Pond as evidence for the absence or rarity of fire in the local area. We disagree and think that the consistent presence of microcharcoal observed throughout the Maple Pond sequence may indeed reflect relatively frequent, low-intensity fire regimes characteristic of pre-European settlement fire-adapted Appalachian forests (Lafon et al., 2017; Chapter 4, p. 58). Low intensity fires reflective of indigenous burning, lightning strikes, and warm conditions, would likely have swept across the edaphically dry alluvial fans that underly the Maple Flats pond complex throughout much of the Holocene. However, charcoal accumulation in lacustrine environments reflects a composite signal of fire occurrence and taphonomic processes governing charcoal production, transport, and deposition (Whitlock & Larn, 2001). For example, the flat areas around the three ponds in Maple Flats (Spring, Twin, and Maple) could reduce the influx of charcoal into the basins. Or Maple Pond's geomorphic position nearer to the slopes of the Blue Ridge, may have facilitated enhanced charcoal influx via upslope combustion or erosional remobilization relative to the more distal locations of Twin Pond and Spring Pond within the sinkhole complex. Furthermore, disparities in basin morphology, catchment area, and local vegetation composition can modulate charcoal accumulation rates between neighboring localities, even under similar regional fire regimes (Sugita et al., 1997). The regional synthesis of Appalachian fire history by Lafon et al. (2017) documents considerable spatial variability in charcoal records across the central Appalachian region, thereby supporting the interpretation that local factors substantially modulate the fire signal preserved within individual sedimentary archives.

Interpretation of the Maple Pond charcoal record requires acknowledgement of the complexities inherent in sedimentary charcoal analysis. One radiocarbon determination form 48 cm depth, coinciding with the interval of elevated charcoal concentrations, was excluded from the age model due to a suspected laboratory handling error (identical result to the sample at 103 cm depth). Additionally, the date at 81 cm (10,250 ± 40 ^{14}C yr BP) yielded an anomalously old age relative to the underlying determination at 103 cm (9,640 ± 40 ^{14}C yr BP), creating a stratigraphic inversion. This age reversal likely reflects the incorporation of reworked charcoal remobilized from watershed soils rather than in situ fire activity. The absence of bioturbation indicators in the core (flat laminations, absence of shells or mixing indicators) supports the interpretation that older charcoal material was transported downslope and redeposited in the basin during erosional events rather than displaced vertically through sediment mixing (Higuera et al., 2007). At sites where anomalously old radiocarbon ages coincide with charcoal peaks, the remobilization of pre-existing charcoal from watershed soils during erosional events presents an alternative mechanism to contemporaneous fire occurrence (Vachula et al., 2024). However, the regional correspondence with elevated charcoal at comparable temporal intervals suggests that the Maple Pond signal may also reflect a genuine increase in regional fire activity.

Mid-to-Late-Holocene (6,000 cal yr BP-present)

During the mid-to-late Holocene (6,000-3,000 cal yr BP), charcoal concentrations declined to background levels, organic content remained moderate (15-25% LOI), and C:N ratios ranged from approximately 10-20 within the mixed-source zone, indicating a shift toward increased contributions form aquatic and wetland vegetation relative to the terrestrial-dominated signatures

(C:N >20) of the Late Pleistocene and early Holocene. This shift toward lower C:N ratios indicates that beginning approximately 8,000 cal yr BP, Maple Pond received increased organic matter from nitrogen-rich aquatic sources, consistent with the establishment of a more productive wetland system. Regional climate reconstructions indicate that the mid-Holocene was characterized by warmer and more arid conditions than present across the eastern United States (Shuman et al., 2009), which may have enhanced pond productivity and promoted the proliferation of emergent wetland vegetation.

During the Late Holocene (<3,000 cal yr BP), the upper core section was characterized by minimal charcoal concentrations, elevated organic content (35-40% LOI), C:N ratios declining to 11-17, and $\delta^{13}C$ values of approximately -27‰ to -28‰, indicating sustained dominance of aquatic and wetland vegetation with enhanced organic accumulation. The declining C:N ratios in the uppermost sediments indicate nitrogen-rich wetland vegetation, likely encompassing helophytic macrophytes and aquatic plants that characterize modern sinkhole pond margins in the Shenandoah Valley (Buhlmann et al., 1999). The contemporary vegetation assemblage around Maple Pond includes *Carex*, *Juncus*, and the federally endangered swamp pink (*Helonias bullata*), and organic matter derived from such wetland assemblages produces the intermediate C:N values observed in the late Holocene sediments.

The pattern of enhanced aquatic influence throughout the mid-to-late Holocene is consistent with regional records documenting wetland expansion across the central Appalachian region (Goodman & Smith, 2023). This trend of increasing organic content and decreasing C:N ratios through the

Holocene characterizes numerous wetland stratigraphies in the region and reflect the long-term development of peat-forming systems following the establishment of modern climatic conditions.

Summary of Environmental Evolution

The geochemical, stratigraphic, and macrocharcoal proxies from Maple Pond collectively document a long history of ecological and depositional stability punctuated by discrete disturbance episodes, capturing the persistence of a wetland system spanning at least the last 15,000 years. The isotopic values (-29‰ to -27‰) and C:N ratios in older sediments indicate that terrestrial C_3 vegetation dominated organic matter input throughout the Late Pleistocene and early Holocene, eventually yielding to nitrogen-rich wetland and aquatic vegetation in the late Holocene. Decreasing mineral content coupled with increasing organic matter up-core reflects a shift from Late Pleistocene minerogenic deposition to sustained Holocene organic accumulation. This pattern mirrors regional trends documented at other central Appalachian ponds and wetlands. The gradual nature of organic content changes throughout most of the core suggests relatively continuous sediment accumulation without major erosional unconformities, consistent with the stratigraphic interpretations of other sinkhole pond systems in the Valley and Ridge physiographic province (Kneller & Peteet, 1993). Carbonate content, estimated from mass loss between 550°C and 1000°C, remained consistently low throughout the core, generally comprising less than 5% of sediment dry mass. This minimal carbonate fraction contrasts with marl-rich sequences documented at some nearby central Appalachian sites, such as Browns Pond (Kneller & Peteet, 1993). Although Maple Pond developed within a carbonate karst depression, sediments at this site contain low calcium carbonate, indicating that deposition is dominated by siliciclastic colluvium derived from Antietam quartzite on the surrounding slopes (Buhlmann et al., 1999).

Although climatic conditions exhibited considerable variability across the Late Pleistocene and Holocene intervals (Vachula et al., 2024), Maple Pond preserves a continuous stratigraphic record of organic deposition and frequent, low-intensity fire regimes. Data derived from Maple Pond demonstrates parallels with paleoenvironmental reconstructions obtained from Cranberry Glades (Watts 1979), Brown Pond (Kneller & Peteet, 1993, 1999), Spring Pond Craig, 1969), and Twin Pond (Vachula et al., 2024). These spatial and temporal correspondences indicate that sinkhole wetland systems throughout the Shenandoah Valley underwent analogous paleoenvironmental trajectories, thereby substantiating the utility of these basins as long-term paleoenvironmental records (Buhlmann et el., 1999) documenting major central Appalachian climatic transitions.

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