

Hidden legacies: Investigating buried pre-colonial stream corridors in the Mid-Atlantic Coastal Plain, Maryland, USA[☆]

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ABSTRACT

Within the Mid-Atlantic United States, widespread landscape disturbance during European colonization resulted in erosion and subsequent storage of legacy sediments within river valleys and floodplains, altering their form, function, and flora. Previous studies of precolonial river corridors have influenced river restoration designs and targets throughout the region, but the generalizability of these studies into other physiographic settings, such as the Coastal Plain, is unknown. Therefore, our study investigated the physical form and riparian vegetation of pre-colonial stream corridors located within the Coastal Plain of Anne Arundel County, Maryland, documenting changes from pre- to colonial and postcolonial time periods. Our study provides evidence of buried, precolonial riparian ecosystems with dates ranging between 750 years to 8000 years Before Present. These valley bottom ecosystems were likely a dynamic patch mosaic, largely dominated by dense *Alnus* (alder) scrub swamps with variable Poaceae (grass) and Cyperaceae (sedge) dominated meadows and both multi-threaded and single-threaded channel forms. These precolonial floodplains are buried by vast amounts of legacy sediment to the extent that pre-colonial sediments are largely not exposed in the modern valley bottom. Notably, the Coastal Plain precolonial corridors investigated in this study contrast to studies in the Piedmont physiographic region with precolonial sediments exposed in streambanks and with precolonial ecosystems described as herbaceous stream-wetlands. Our findings provide critical historical context as to the magnitude of alteration for modern stream channels and suggest an alternative precolonial ecosystem which can be used to inform restoration designs, management targets, and reestablishment of channel functional processes in areas of the Mid-Atlantic Coastal Plain.

1. Introduction

The Chesapeake Bay is the largest estuary in the United States and was home to early English colonies during the European colonization of the Atlantic Coast of North America. A variety of disturbances from the colonial and subsequent eras (hereafter, together referred to as ‘post-colonial’) resulted in widescale changes to the landscape and river corridors in the region. These changes can continue to affect environmental conditions through the modern era – a concept known as environmental “legacies” (James, 2018; Wohl, 2015a). These legacy effects

can change the physical forms and geomorphic processes of river corridors (James, 2018) but also the composition and function of floral and faunal communities (Ellis, 2021; Ellis et al., 2010; Maloney and Weller, 2011).

Postcolonial agriculture, forest clearing, and mining resulted in historically elevated rates of watershed sediment delivery to stream corridors and the accumulation of legacy sediment, the term widely used to refer to historical sedimentation associated with human impacts (James, 2018; Wohl, 2015a). Excess sediment in stream channels and valley corridors is widely recognized as an historical and contemporary

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problem for resource managers in the Chesapeake Bay watershed (Noe et al., 2020) and a factor in regionally pervasive physical habitat alterations (Cashman et al., 2024). Together, excess sediment in waterways and related alterations of habitat conditions are among the top instream stressors causing local ecological impairment in the Chesapeake Bay watershed (Fanelli et al., 2022). In addition, much of this excess instream sediment has been shown to be sourced from the erosion of channels with notable fractions of legacy sediment (Cashman et al., 2018; Clifton et al., 2022; Gellis and Gorman Sanisaca, 2018).

At many locations where legacy sediment has been studied in the Chesapeake region, the demarcation between pre- and postcolonial sediments is distinctly visible within exposed streambanks, making the magnitude of legacy sediment accumulation evident (Donovan et al., 2015; Hupp et al., 2013; Noe et al., 2020; Pizzuto et al., 2024; Walter and Merritts, 2008; Wolman, 1955). Yet a visual marker gives little direct quantifiable data on the pre-disturbance state, only that there has been a qualitative change (Antonelli et al., 2024). In addition, many legacies can persist with little obvious visible evidence, as time, natural processes, and subsequent changes can hide or modify the initial disturbance (Cashman et al., 2021; Cristol et al., 2008; East et al., 2018). Overall, it is particularly challenging to quantify the magnitude of historical disturbances which occurred centuries ago, often prior to instrumented records, and which have missing or incomplete data (Bain et al., 2012). As a result, our understanding of most historical legacies is affected by shifting baseline syndrome (Humphries and Winemiller, 2009; Soga and Gaston, 2018), whereby the original state of an ecosystem, and its changes, are largely forgotten. Forgotten legacies not only include local flora and fauna, but the structural forms and associated ecological, geomorphic, and hydrologic functions and processes that undisturbed ecosystems might provide (Wohl, 2019). As this can result in altered perspectives of the natural form, aesthetics, and function of aquatic and riparian landscapes (Wohl and Merritts, 2007), this has profound relevance to the references and targets of ecological restoration (Barak and Katz, 2015; Cronon, 1996; Cross et al., 2019; Humphries and Winemiller, 2009; Stanford et al., 2018) and their acceptance by the public (Chin et al., 2008). To address these issues, the investigation of past ecological conditions, and evaluating trajectories of change, provides valuable context to guide management decision making and the selection of ecological conditions and processes for restoration (Wingard et al., 2017).

Paleoecological studies of the Piedmont Physiographic Province in the Chesapeake watershed have suggested that, prior to European colonization, anastomosing stream/wetland complexes were ubiquitous in valley bottoms (Elliott et al., 2013; Merritts et al., 2011; Walter and Merritts, 2008). In contrast to the modern conception of a reference, single-threaded stream channel with banks lined with riparian trees, these precolonial corridors were hypothesized to be stream-wetland complexes typified by small, vegetated, branching channels with a plant community dominated by herbaceous wetland species that thrive in saturated soils. Subsequent colonial land-use changes, primarily due to agriculture and forest clearing at a cottage and industrial scale (Besley, 1915) – and exacerbated by enhanced sediment retention from millpond development – led to the paleo-streams and valley bottoms being buried by legacy sediment. As the industries driving these land use patterns of elevated sediment yields declined over the twentieth century (Wolman, 1967), Mid-Atlantic valley bottoms shifted from net depositional to net erosional, producing the present-day, single-threaded incised channel (Merritts et al., 2011; Walter and Merritts, 2008).

Due to these findings, precolonial herbaceous stream-wetland complexes have been used as a reference ecosystem for restoration designs which attempt to excavate legacy sediment and restore the modern-day single threaded channel into a stream-wetland complex (Baltzer et al., 2024; Hartranft et al., 2011; Langland, 2015; Smith et al., 2020). However, the paleoecological studies informing these designs have predominantly occurred within the Piedmont physiographic province, a region of rolling hills and erodible silty upland soils that stretch across

much of the East Coast of the USA (Bascom, 1921). The question remains whether the findings of precolonial stream ecosystems in the Piedmont are generalizable to other nearby physiographic provinces. Namely, there has been growing management interest to apply the restoration designs based on the Piedmont reference stream-wetland complex ecosystem into other physiographic provinces, including the low-gradient Coastal Plain, where the paleogeomorphology and paleoecology of small streams are poorly described.

Distinct from the Piedmont in its topography, geology, hydrology, ecology, and colonial history, the Coastal Plain may also have profound differences in its precolonial ecosystems and the magnitude and visibility of its colonial legacies. The flattest physiographic province in the United States, the Coastal Plain is typified by large tidal rivers, low-gradient streams, and underlain by a wedge of unconsolidated sediments, the product of tens of millions of years of erosion off higher inland Appalachian landscapes (Ator et al., 2005). In the Chesapeake region, it also features numerous small tributaries that feed directly into tidal tributaries along the Chesapeake Bay perimeter. Without understanding these differences, an application of findings from the Piedmont may lead to potentially inconsistent, inappropriate, or otherwise out of context restoration targets for the Coastal Plain. Paleoecological investigations specifically for the Coastal Plain are therefore needed to provide more regionally relevant historical and environmental data to inform management efforts and ecological restoration in the region.

1.1. Research purpose and objectives

The purpose of this work was to inform river managers and restoration practitioners on the structure and ecology of the pre-colonial stream environment in the Anne Arundel County Coastal Plain, so that they may use “the past as a guide to future decision making” (Wingard et al., 2017). A better understanding of the pre-colonial stream corridor ecosystem, including its riparian flora, would help support restoration efforts in the region by providing important contextual information for the applicability of different stream restoration designs and dominant processes or stream functions to restore. In addition, this supports public outreach by providing information on how local stream environments once looked and how current restoration designs relate to those historical patterns, even if they differ from the current landscape or the public’s expectation of a natural river.

Therefore, the overarching objective of this study was to extend investigations of the structure and ecology of pre-colonial streams into the Atlantic Coastal Plain of Maryland, USA, and document the extent of postcolonial historical changes in valley bottoms. A secondary objective was to then compare our findings to the prevailing ecological reference system based in the Piedmont which currently influences restoration designs.

We hypothesized that we would find:

- A) An obvious visible transition in soil characteristics between pre-colonial to postcolonial legacy sediment exposed in streambanks as found in other nearby provinces.
- B) Evidence of a precolonial stream corridor ecosystem distinct from the modern-day stream corridor, as indicated by differences in the riparian plant communities found in the pollen record and/or channel structure determined by geophysical exploration.
- C) Notable differences between precolonial ecosystems in the Anne Arundel County Coastal Plain *versus* those proposed in the Piedmont which are relevant to management and restoration designs. Specifically, we expected to find a more woody-dominant swamp ecosystem and with spatial and temporal variability according to patch dynamics and disturbance theory.

2. Methods

2.1. Study area

Anne Arundel County is in central Maryland, USA, south of Baltimore City, and contains the city of Annapolis, the modern Maryland state capitol (Fig. 1). Covering an area of 1520 km², the county has a humid subtropical climate with average annual (1895–2019) air temperatures ranging from 7 °C to 18 °C and year-round rainfall averaging 1110 mm annually (PRISM Climate Group, 2023). The eastern edge of Anne Arundel County is a highly crenulated coastline, with multiple small drainages to the Chesapeake Bay, the largest estuary in the United States. The County also encompasses several large tidal rivers and inlets, including the South, Severn, Magothy Rivers, and part of the Patuxent River (Fig. 1).

Anne Arundel County is located predominantly within the Mid-Atlantic Coastal Plain, where streams are generally low-energy (mean slope: 0.27 ± 0.4 %; McKay et al., 2012), with silt-sand streambeds and steep streambanks leading to broad floodplains (Kirby and Matthews, 1973). The Coastal Plain is underlain chiefly by complexly stratified unconsolidated sediments deposits of gravel, sand, silt, and clay. These range in thickness from a dozen meters along the northwestern boundary to as much as ~550 m in some eastern sections (Vroblecky and Fleck, 1991) and age from the early Cretaceous to recent (Andreasen, 2007).

2.2. Methodological approach

To address the complex nature of investigating historical legacies across multiple spatiotemporal scales, we employed a comprehensive multi-scale, multi-method approach in line with the framework for studying legacy effects proposed by Antonelli et al. (2024). This methodology leverages a diverse range of historical and contemporary sources providing information at different spatiotemporal scales and reliability, including primary source historical records, secondary historical reviews, cartographic products, remote sensing, localized field investigations, and paleoecological data. These sources provide information conducive to both anticipative and retrospective approaches for investigating anthropogenic legacies (Antonelli et al., 2024). For example, information on historical conditions or drivers of disturbance suggests a possible legacy of change (*i.e.* anticipative approach), whereas contemporary conditions may provide more direct indication of past legacy changes but without indications of the cause or pre-disturbance condition (*i.e.* retrospective approach). Together, this multi-source and multi-scale methodology provides a weight-of-evidence approach to understand and contextualize the paleo-hydrology, -geomorphology, and -ecology of precolonial river corridors and subsequent legacy changes.

We systematically treated data sources using a spatially nested approach, beginning with regional and county-wide data sources and progressively refining our spatial focus to more targeted, spatially limited data sources which provided more robust and directly quantifiable data. Specifically, our methodological approach followed these steps: 1) a review of colonial written records and secondary historical literature of the region and county; 2) a desktop-based county-wide exploration of cartographic and remote sensing sources; 3) preliminary field-based reconnaissance at a range of sites across the county; 4) focused field-based investigations at a limited number of sites. This iterative process not only identified specific sites for further investigation but also facilitated the contextualization and potential generalization of findings from individual sites back to regional patterns.

2.3. Written and historical records

County library, historical society, state archives, and other related online archives and repositories were searched for relevant information on precolonial or early colonial conditions of the Maryland Coastal Plain

and specifically Anne Arundel County. Topical areas considered included descriptions of flora and fauna, erosion, beaver, navigation, agriculture, and trade. This included review of the writings of John Smith's initial explorations of the Chesapeake, with a narrow focus on writings about the Maryland coast (Smith, 1624), and other compilations of letters, writings, and other narratives from and about early Maryland (Hall, 1910). In addition, legislative records from early colonial Maryland were also evaluated (Archives of Maryland, 2024).

2.4. Desktop reconnaissance and site identification

The county-wide desktop reconnaissance process evaluated various historical mapping products and conducted remote-sensing analyses to survey and characterize conditions throughout Anne Arundel County. This approach aimed to identify sites with either direct or indirect evidence of potential legacy effects along the stream corridor, which were then cross-validated with additional site-specific historical and contemporary records.

Initially, site reconnaissance was stratified across the county using discrete watershed segments developed for the county's biological monitoring program. These watershed units, called primary sampling units (PSUs), were derived from the state of Maryland's 8-digit watershed units (Hill and Stribling, 2004). Within each PSU, various data sources were evaluated to identify sites with potential legacies according to a range of criteria: topographic conditions identified in GIS analyses, changes within the river corridor based on historical mapping products, locations of active management or stream restorations chosen due to modern degraded or incised site conditions, and other associated site-specific historical records, as described below. A minimum of one site containing potential evidence of legacy changes was identified for each PSU; this process was not exhaustive to identify all potential locations of legacy changes throughout the county.

For remote-sensing analyses, lidar-derived county-wide digital elevation models (DEMs) for 2011 and 2017 were obtained from the Maryland iMAP lidar server portal (Maryland iMAP). A 1-m resolution DEM of difference between 2011 and 2017 was calculated in ArcGIS⁺ (ESRI, Redlands California) to identify areas of erosion and other topographic changes in vertical elevation. A slope raster and hillshade were derived from the 2017 DEM in order to visually identify sharp topographic changes. The 2017 DEM was further classified into 10 discrete local terrain geomorphic units, called geomorphons, using the *r.geomorphon* package (Jasiewicz and Stepinski, 2013) in GRASS GIS⁺ (Neteler and Mitasova, 2002). Across all these data sources, qualifying criteria included retrospective evidence of legacy change such as the presence of incised, eroding streambanks especially in flat valley bottoms, breaks in valley elevation and slope due to impoundments, and longitudinal discontinuities in the expected geomorphon valley and depression classifications in the traditional valley bottom (*i.e.* indicative of historical impoundments, high magnitudes of floodplain sediment deposition, or historical, abandoned channel forms). Qualifying criteria for anticipatory evidence included colonial activities visible in topography that could be drivers of legacy changes (*e.g.*, abandoned mill, other dam, colonial structures, or historical road embankments).

Historical mapping products for the region were compiled and examined, including historical maps from 1795 through 1878 (Griffith et al., 1795; Hopkins, 1878; Martenet et al., 1860; Sotzmann et al., 1797), historical aerial imagery acquired throughout the 20th century, historical nautical charts from the mid-19th century to present (NOAA, 2025), and US Geological Survey topoquads dating to the late 19th century (Allord et al., 2014). Possible legacy changes were identified by evaluating changes in stream positioning and/or changes in wetland or open water extent (*e.g.*, shrinking/loss of wetlands, or creation and/or loss of pond/open water on the stream channel or at the channel mouth). Especially given the spatial uncertainties and other inconsistencies in historical map data, evaluations of change were made in comparison to fixed reference locations, such as distinct valley margins or

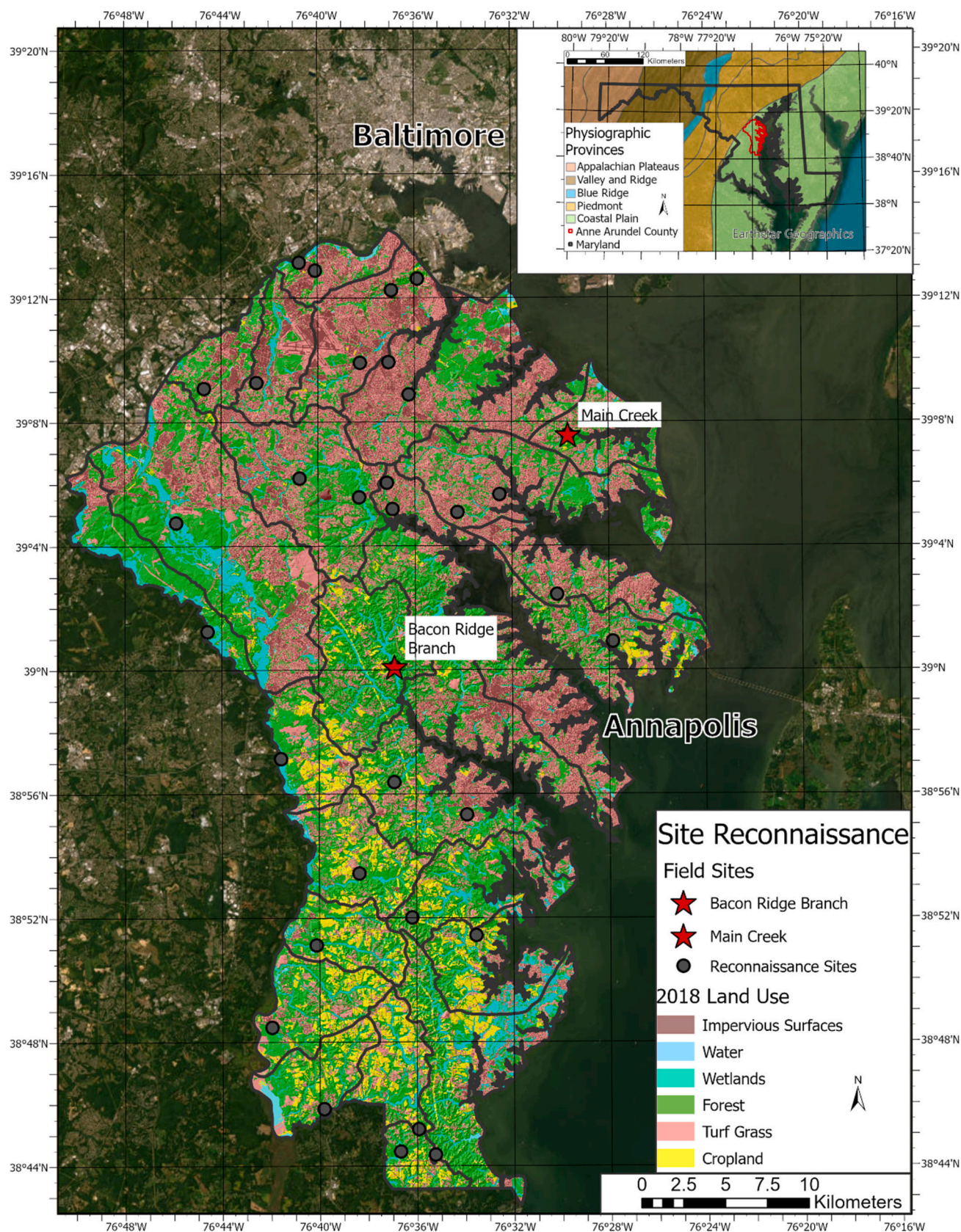


Fig. 1. (Inset) Study area relative to the state of Maryland and physiographic provinces in the Mid-Atlantic region. (Main) The spatial distribution of sites visited during site reconnaissance, overlaid with 2018 1-m landuse/landcover and a hillshade constructed using lidar from 2017. The final study sites selected are highlighted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

constrictions, tributary confluences, and/or road crossings, and whether evidence of change was corroborated over multiple mapping products.

Lastly, candidate sites with potential evidence of legacy effects were cross-compared to historical records of land use in local and upstream areas that might anticipate legacy effects in the stream corridor (e.g., dams, towns, farms, etc.). In addition, sites were cross-referenced in Maryland's Inventory of Historic Properties (MIHP) and in county library, historical society, state archives, and other affiliated resources for additional contextual information about the specific land-use and contextual setting of those locations and watersheds.

2.5. Preliminary field based exploration

Sites initially identified from desktop reconnaissance for potential legacy effects were then visited for a field-based verification of legacy effects, continuing with the stratified process of at least one site visited per PSU. Field visits were done to confirm the patterns initially identified by the desktop analysis, and specifically to look for field-evidence of historically lower floodplain surfaces and the presence of conditions which could be used to quantitatively evaluate legacy changes. We evaluated sediment stratigraphy in exposed streambanks and beneath the modern channel using test augers to identify distinct visual and textual changes in sediment stratigraphy, identify buried organic hydric strata, and evaluate the presence of leaf litter macrofossils in buried sediment strata.

In addition, we examined the presence of "in place", *in situ* tree stumps, determined to be emerging from the modern streambed, as an indicator of a historically lower floodplain surface. Stumps were determined to be *in situ* by examining position, basal flare, and root structure to determine that stumps were not fluvially deposited and rather suggest growth from a formerly lower-elevation valley bottom surface, which was previously buried and later exposed. Select wood samples were collected and sent for identification by microscopic morphology at the US Forest Service Forest Products Laboratory in Madison, Wisconsin, and through DNA barcoding. Subsamples from a select number of *in situ* stumps were then dated using accelerator mass spectrometry (AMS) radiocarbon dating (see Radiocarbon Dating section below).

At a subset of candidate sites where visits suggested multiple lines of evidence for the possible discovery of precolonial sediment, namely the occurrence of organic hydric sediment strata, observed litter macrofossils recovered in shallow core samples, and the presence of *in-situ* tree stumps, test auger sediment samples were also analyzed for pollen (see section 2.6.3 Pollen Analysis below).

2.6. Focused field investigations

From all sites visited in the preliminary field-based exploration, two sites were selected for focused field investigation to more fully document the potential precolonial environment and quantify the history of legacy changes. These two streams (Main Creek and Bacon Ridge Branch) were chosen because of their representative conditions of multiple sites identified throughout the region, a long-documented history of settlement (both pre-European and colonial) in their respective watersheds, incised streambanks exposing visual changes in sediment profile, presence of *in-situ* buried stumps, and the confirmed presence of macrofossils and preliminary pollen analysis indicating precolonial to postcolonial changes within streambanks and/or shallow core samples. Their drainage areas are consistent with the numerous small and medium watersheds originating in the Coastal Plain and draining to the tidal estuary (4.1 km² and 21.9 km² respectively for Main Creek and Bacon Ridge Branch) and are representative of the county's modern-day mixed land cover (ranging from 6 to 10 % impervious surfaces, 0–8 % cropland, 48–60 % forest, and 18–40 % turf/mixed open; See Supplemental 1). At each site, an approximately 1 km long river corridor segment was selected to characterize historical changes by using ground-penetrating radar (GPR) and floodplain sediment coring to

identify soil stratigraphy, analyze pollen composition, and provide strata-specific radiocarbon dates.

2.6.1. Core analysis

Sediment cores were collected using either a vibracorer with a 4" diameter aluminum core barrel or a 'Russian' peat auger based on ease of soil penetration, following previous studies for collection of sediment cores along riparian corridors (Noe et al., 2016). Cores were collected until encountering resistance at depth, and degree of compaction was measured based on difference between the depth of the core hole and length of the core. Seven sediment cores were collected each from Main Creek (1 vibracore/6 peat auger) and Bacon Ridge Branch (5 vibracore/2 peat auger; Table 1; Supplemental Fig. S1).

Cores were scanned at the USGS Florence Bascom Geosciences Center in Reston, Virginia on a GeoTek core scanner* (Northamptonshire, United Kingdom) for imagery and at a 0.5 cm sampling resolution for color, magnetic susceptibility, near-VIS/UV spectra, and X-Ray fluorescence-derived soil geochemistry. Imagery was collected with a Geotek GeoScan V Linescan*. Magnetic susceptibility was collected with a 100 mm diameter Bartington MS2C* loop sensor and an MS2E* point sensor (Bartington Instruments, Witney, United Kingdom) with 10 s dwell times. Measurements of reflectance at visible (400 to 700 nm) and near-infrared spectra (750 to 2500 nm), as well as grey-scale, CIE XYZ colorspace, and CIE L*a*b* colorspace values were collected with a Malvern Panalytical ASD LabSpec* (ASD, Westborough, Massachusetts, USA). All Geotek procedures followed the manufacturer's manual (Geotek Ltd., 2023). Soil geochemistry was quantified with a mounted Olympus Vanta M Series handheld XRF* (Olympus ANI, Waltham, Massachusetts, USA), with a measurement time of 30 s per beam following manufacturer's methods (Olympus/Evident, 2020).

Core colorspace values were interpolated into Munsell color specifications using the R package *munsellinterpol* (Gama et al., 2022) and matched to closest Munsell chips. Munsell chip colors were summarized as percentages of core lengths for pre- and post-colonial sediments identified by pollen analysis and visualized using the R package *Algorithms for quantitative pedology*, *aqp* (Beaudette et al., 2023). Soil geochemistry, color, and magnetism values were then used to evaluate separation and most effective tracers for predicting whether sediments were pre- or post-colonial in origin – as determined by pollen analysis (see section 2.6.3 Pollen Analysis) – according to a linear discriminant analysis using the *MASS* package in R (Ripley et al., 2013). Soil data were Yeo-Johnson transformed (Weisberg, 2001) for multivariate normality.

General lithological types were visually described throughout each core. Select macrofossils were documented in the cores and retained for subsequent radiocarbon dating. Cores were then sampled in 2-cm increments from selected intervals that corresponded with documented lithological changes and analyzed for pollen. Between seven to seventeen samples were taken for pollen analysis per core depending on the length of the core and number of distinct lithological types identified.

2.6.2. Radiocarbon dating

Plant macrofossils sampled from cores were analyzed for accelerator mass spectrometry radiocarbon analysis by Beta Analytic, Inc.*, following standard preparation and measurement techniques (ASTM International, 2022). Radiocarbon dates are reported as calibrated ages in years Before Present (yrs. BP) using BetaCal4.20: HPD method: INTCAL20. In total, thirty-four samples were radiocarbon dated across fourteen cores.

2.6.3. Pollen analysis

Standard preparation techniques (Traverse, 2007) were used to isolate palynomorphs (pollen and spores). A target number of 300 pollen grains and spores were counted from each sample as a representative sampling to determine percent abundance. In limited occurrences, the sample was dominated by an individual palynomorph in counting,

Table 1

Information about all cores obtained at both Study Sites. *Indicates additional depth added due to the core being collected directly in the channel bottom and represents the elevation difference from the elevation of the core and top of bank/floodplain.

Study Site	Core ID	Core Type	Notes	Floodplain Elevation (m NAVD88)	CH Elevation (m NAVD88)	Core Bottom Elevation (m NAVD88)	Penetration Depth (m)	Recovered Length (m)	Compaction (m)
Main Creek	MC-1 V	Vibracore	Downstream, dense roots	1.48	–	0.62		0.86	–
	MC-2R	Russian Peat Corer	Floodplain, swampy soils	2.23	1.08	0.47	1.76	1.76	–
	MC-3R	Russian Peat Corer	Most downstream core	1.25	–0.50	–0.95	2.20	2.20	–
	MC-4R	Russian Peat Corer	Floodplain, 3 m from creek, incised channel	5.42	4.37	4.05	1.37	1.37	–
	MC-5R	Russian Peat Corer	Floodplain, 3 m from creek, incised channel	6.7	5.65	5.05	1.65	1.65	–
	MC-6R	Russian Peat Corer	Most upstream core, 4 m from creek, low banks	8.3	–	7.33	0.97	0.97	–
	MC-7R	Russian Peat Corer	Floodplain, 4 m from creek, swampy soils	5.15	3.90	3.66	1.49	1.49	0
	BRB-1 V	Vibracore	Floodplain, 6 m from river, dry soils	2.79	0.37	–0.06	2.85	2.12	0.73
	BRB-2 V	Vibracore	Along lower side-tributary, near confluence	2.11			Discarded due to poor recovery		
	BRB-3 V	Vibracore	Floodplain, wet depression	1.94	–	–0.66	2.60	1.79	0.81
Bacon Ridge Branch	BRB-3R	Russian Peat Corer	Floodplain, wet depression ~4 m adjacent to 3 V	1.96	–	0.77	1.19	1.19	–
	BRB-4 V	Vibracore	In tributary stream bed, 1.7 m beneath top of bank	5.39	1.93	1.06	2.63 + 1.7*	2.24	0.39
	BRB-5 V	Vibracore	Floodplain, grassy clearing	1.26	–	–1.17	2.43	1.88	0.55
	BRB-5R	Russian Peat Corer	Floodplain, grassy clearing, ~3 m adjacent to 5 V	1.27	–	–0.13	1.40	1.40	~0
	BRB-6R	Russian Peat Corer	Upstream floodplain, low banks, swampy soils"	2.88	0.28	–1.92	4.80	4.80	~0

which may occur due to the interaction of species-specific pollen output volume, preservation, dispersal methods of pollen types, and specific coring location. In this case, counting continued until a minimum of 100 non-dominant palynomorphs were identified.

For reporting purposes, the majority of taxa were grouped into one of three vegetation categories: woody, herbaceous, or fern. Key taxa included in the woody category included *Alnus* (alder), *Carya* (hickory), Cupressaceae (cypress family), *Fraxinus* (ash), and *Nyssa* (tupelo) with a minor presence of *Acer* (maple), *Betula* (birch), *Ilex* (holly), *Juglans* (walnut), *Ostrya/Carpinus* (hornbeam), *Liriodendron* (tulip tree), *Morella* (wax myrtle/bayberry), and *Ulmus* (elm). *Quercus* (oak) was not included in the woody sum as oak trees often represent regional pollen input rather than local site conditions; oaks are wind-pollinated and copious pollen producers, with dispersal distances of 30 km or more depending on local atmospheric conditions (Schueler and Schlünzen, 2006). Similarly, *Pinus* (pine), a gymnosperm, also primarily reflect the regional pollen input as *Pinus* are wind-pollinated tree taxa with high pollen production and significant dispersal distances. Key taxa included in the herbaceous category were *Cephalanthus* (buttonbush), *Nuphar* (waterlily), Ericaceae (heaths/low-bush berries), and *Typha* (cattails), with secondary taxa representing various Euphorbiaceae and Fabaceae taxa. Although *Cephalanthus* and Ericaceae are woody plants, we included them in the herbaceous category in recognition of their lower vertical structural profiles consistent with other herbaceous taxa. Other key herbaceous taxa related to anthropogenic/agricultural farming practices include *Nicotiana* (tobacco), *Humulus* (hop), *Plantago* (plantain/fleawort), *Rumex* (sorrel), and *Zea mays* (corn). Asteraceae

indeterminate and *Ambrosia* (ragweed), as well as Poaceae (grasses) and Cyperaceae (sedges) were not included in the herbaceous sum. Ferns, a key understory element, were given their own summary grouping and included *Osmunda* and other indeterminate fern taxa.

The Asteraceae family, particularly the genus *Ambrosia* (ragweed), serves as an indicator of land disturbance (Brush, 1984). Its appearance and increased prevalence were used to establish a before/after threshold of large-scale land disturbance and agricultural intensification resulting from European colonization, hereafter referred to as the Colonial Horizon (CH). Sediments at depths beneath the CH were considered precolonial, while sediments at depths above the CH were considered postcolonial.

Pollen Zones (PZ) were then created using full pollen composition data through a combination of visual inspection and stratigraphically constrained cluster analyses in CONISS (Grimm, 1987). A full listing of taxonomic units is contained in Supplementary Table 1 and all raw pollen counts are available through the associated data release at Clifton et al. (2023).

2.6.4. Ground penetrating radar survey

To assess potential changes to the structure of the local channel planform, we collected a total of 15 cross-sectional transects and two longitudinal transects with GPR between the two study sites. GPR survey transects were collected in September and October 2021 with a MALÅ* GX450 HDR unit (Guideline Geo; Summerville, South Carolina, USA) featuring a 450 MHz antenna for shallow investigations. Due to rough land surface and dense vegetation, a sample rate of 1 point per 0.002 m

was used to improve measurement resolution. At each study site, transects were conducted orthogonal to the main channel, from valley wall to valley wall, and intersected with the approximate locations where sediment cores were collected. Cross-valley transects were also conducted between sediment core locations where the distance between sediment cores exceeded 400 m. A single longitudinal transect running roughly parallel to the main channel was also surveyed for each site between the upstream-most and downstream-most sediment core locations.

After collection, GPR survey data were offloaded from the MALA* unit and input into ReflexW* (Sandmeier Geophysical Research; Karlsruhe, Germany) for GPR processing and interpretation. Each transect survey was processed following the same general procedure as defined by the ReflexW manual, with minor variations according to conditions identified in the data itself in accordance with similar studies in lowland floodplains (e.g., Słowik, 2011). The processing procedure followed: (1) a dewow filter; (2) a Butterworth-style bandpass filter; (3) a static correction to compensate for the time delay of the first signal arrival; (4) the application of gain proportional to signal attenuation (an “Energy Decay” gain); (5) removal of clutter attributable to system noise with a subtracting average trace; and (6) increase the signal to noise ratio by stacking traces.

After processing, soil layers were identified in the resulting radargrams and average soil velocities for each layer were determined by manually fitting the convexity of at least ten hyperbolas to those identified in the radargrams (Huisman et al., 2003). Soil layers were then matched to the sediment stratigraphy, including CH, identified by the core results (described above) at core-locations that overlapped with GPR transects. These distinct soil layer transitions were then traced through the GPR survey. Depths to soil layers and their spatial location were then exported to ArcGIS* v2.6.2 (ESRI, Redlands, California, USA) to identify the depth of the horizon perpendicular across the valley and longitudinally down the study site.

3. Results

3.1. Historical records

Human presence in the county dates to as early as ~10,000 yrs. BP when early indigenous hunter-gatherer tribes settled the area, and evidence of subsistence agriculture dates to between 500 CE and 1000 CE (Ebright, 1992). The county was settled by European colonists in 1650, 18 years after the establishment of the Maryland colony, and Annapolis became the colonial capitol in 1694. Early settlements and plantations in Anne Arundel County were located primarily along sheltered waterfronts, coves, and inlets, with each settler having tidewater access for transporting goods by boat (Gottschalk, 1945a).

Colonists described the coastal regions of the Chesapeake Bay adjacent to Anne Arundel County as rich with swamps, springs, meadows, with hearty organic-rich soil over two feet in depth (Hawks, 1635; Smith, 1624; White, 1633). Early accounts note the abundance of beaver in local waterways (Hawks, 1635), with early Maryland controversies centered on disputes regarding the lucrative fur trade, including beaver pelts (Jonas, 1966). The Maryland General Assembly in Annapolis installed duties on beaver pelts to fund schools as early as 1695 (Maryland General Assembly, 1695), and as a testament to beaver ubiquity in Anne Arundel County, a property assessment index from 1783 features over twenty instances of properties featuring the phrase “Beaver Dam” (Maryland State Archives, 1783).

Colonial agricultural practices contributed to exhaustion and erosion of local topsoil, driving further agricultural expansion to areas with intact soils, resulting in substantial clearing of old-growth forests throughout the 1700s (Besley, 1915). Agriculture peaked in 1850 at 59 % of the land area of the county (Hagan, 2025; US Census Bureau, 1853; US Census Bureau, 1870; Walker, 1870). Demand for shipbuilding in the nearby seaports led to additional clearing of hardwood forests in the

later 1700s and beyond (Ford, 2001). Anne Arundel County was the most heavily populated English county in North America by the end of the 17th century and its population doubled in size roughly every twenty-five years from the late 17th century through the end of the 18th century (Ware, 1990), suggesting rapid changes to the local landscape.

3.2. Desktop-based site exploration and selection

Mill dam impoundments were abundant throughout the county, with at least 20 dams evident on historical maps as early as 1794 (Griffith et al., 1795). Mill dams were associated with highly incised channels in the dam impoundment, which was visually evident in the DEM. However, the presence of dams was not required for many legacy changes seen throughout the county-wide desktop analysis, and thus did not become a dominant focal point of selection.

Overall, across the 24 PSUs, 53 candidate sites were identified from the desktop reconnaissance due to potential legacy effects. Thirty-two sites featured evidence for legacy effects visible in remotely sensed topography and/or historical maps; of those, five had visible historical dam structures and thirty-two had historical settlements (pre-1878) within approximately one mile (Supplemental Fig. S1). Thirty-one sites were heavily incised according to visual DEM inspection. Apparent change to coastal outlines in tidal rivers, wetlands, and open water were also evident in historical topoquads and maps, and at least eleven sites showed distinct wetland retreat in historical topoquads and maps. Twenty-one sites had planned stream restorations, and 10 sites were undergoing or had recently completed stream restorations. Sites with ongoing or completed stream restorations that included bank regrading or protection, or channel realignment, were not included in subsequent field-based investigations due to potential large-scale modifications to the soil profile and stream channel, potentially obscuring recovery of precolonial data, legacy effects, and intact stratigraphy.

3.3. County-wide preliminary investigations

Thirty-three sites were visited in the field for preliminary field-based exploration and further verification of legacy effects, continuing with the stratified process of at least one site visited per PSU (Fig. 1).

Of the 33 prospective sites visited in the field across Anne Arundel County, river channels were typically incised with reach-average bank heights of 1.3 ± 0.6 m (mean $\pm$ SD); the maximally incised site had reach-average bank heights of 2.4 m. Site conditions ranged from emergent marsh and wooded scrub swamps to single-threaded channels disconnected from adjacent floodplains. Historic mill dams were identified within 2 km of the visited reach for 5 sites according to historical records and field observations (Supplemental Fig. S1). Beaver activity was noted at 13 sites, mainly evidenced by chewed stumps, although recent activity (i.e., dams or fresh feeding) was only observed at 4 sites. Buried, *in situ* tree stumps, with root flares intact in the stream bed or beneath, were also observed at 15 prospective sites, some of which were also beaver chewed (Supplemental Fig. 1).

Wood anatomical and DNA-derived identification of *in-situ* buried stumps identified several members of the Southern Yellow Pine Group, as well as members of the *Nyssa*, *Fraxinus*, and *Quercus* genera (Supplemental Table S1). Test augers at a subset of sites indicated that changes in soil character and color generally occurred at greater depths than the horizon of the basal flare of these tree stumps. An *Nyssa* stump *in-situ* in the modern stream bed at one site (Fig. 2) dated to 180 ± 30 yrs. BP, while the CH was identified at greater depths (Fig. 3).

Pollen analyses using test augers for four sites showed the CH to be on average nearly two meters below the current valley bottom surface, near or below the modern baseflow water surface, and often below the modern streambed (Fig. 3). Pollen recovered from below the CH reflected a *Quercus* and *Pinus*-dominant forest with high concentrations of either *Alnus* or *Carpinus* and secondary elements of *Nyssa*, *Betula*, and ferns. One site evidenced a pre-colonial plant community that included



Fig. 2. Three in-place wood stumps (indicated by arrows) are exposed in the channel bed of Upper Mill Creek, Maryland, USA, one of the sites examined during county-wide preliminary site investigations. Wood stumps are in place, with existing root structures, and a basal flare roughly corresponding to the stream bed, suggesting these trees were once growing on previously lower elevation floodplain, later buried, and more recently re-exposed due to incision and lateral erosion of the current stream channel. Photograph by Matt Cashman, U.S. Geological Survey.

Ericaceae heath and *Sphagnum* mosses, indicative of a bog community. Pollen assemblages in Postcolonial sediments were dominated by *Quercus*, *Pinus*, *Ambrosia*, *Zea mays*, Poaceae, Ranunculaceae, *Vitis*, Asteraceae, and early postcolonial samples showed a transition between the two communities.

3.4. Focused field intensive site investigations

3.4.1. Main Creek

USGS topoquads and US Coast Survey bathymetric maps dating back to 1857 appear to show the margin of Main Creek's open water area possibly retreating downstream over the last century (Fig. 4). Notably, a small tributary which drains from the north of the study area appears to empty directly into open water in 1857 and through 1893, yet in 1904

and later mapping products is connected to the flowing creek prior to reaching open water areas (Fig. 4).

Like with other sites in the county-wide preliminary investigations, multiple *in-situ* stumps were found in the channel bed at Main Creek. These were identified to *Nyssa* and *Liquidambar*, the latter of which was dated to 220 ± 30 yr. BP, indicating that despite being indicative of a buried floodplain, precolonial sediments were deeper in the soil stratigraphy.

3.4.1.1. Coring results. Six cores were recovered for analysis from the near-channel valley bottom, covering the range of present geomorphic channel conditions in the study area, including both segments with deeply incised channels and lower-banked wetlands with saturated soils (Table 1). Ground surface elevations at core locations ranged from 1.25 to 8.3 m NAVD88, penetration depths varied between 0.86 and 2.20 m, and bottom of cores extended as deep as a maximum of 1 m below the NAVD88 datum (Table 1).

The CH, the demarcation between postcolonial legacy sediments and deeper buried precolonial sediments, was identified in five of six cores due to a rapid shift and disappearance in *Ambrosia* pollen. Precolonial sediments were buried on average ~ 1.2 m below the modern floodplain surface (range: ~ 0.75 m to 1.75 m) and increased in depth down valley along the study area.

Precolonial sediments were predominantly peaty muds or clayey muds, with nearly half of sediments with dark Munsell colors of low chroma, mainly 2.5Y 2/1 to 2.5Y 2.5/1. There were also occasional ($\sim 10\%$) lenses of sand with low-chroma values, ranging from dark gray to blue/white, 10R 4/1 to 5 PB 5/1 (Fig. 5). Radiocarbon dates in precolonial sediment horizons were 2000 yrs. BP, 890 yrs. BP, 740 yrs. BP, and 730 yrs. BP, although three samples found within 25 cm of the CH were dated to 140, 180, and 170 yrs. BP, indicative of likely mixing around the CH (Figs. 6, 7).

Precolonial pollen composition reflect a landscape consisting primarily of a regional mixed forest dominated by *Quercus* and *Pinus*, with more valley-bottom influences of high concentrations of *Alnus*, *Carya*, and *Nyssa* (Fig. 6). *Osmunda* and other ferns dominate the understory vegetation with a minor presence of herbaceous taxa, with some minimal presence of Poaceae and Cyperaceae, and variable amounts of Ericaceae heath (Fig. 6). Precolonial flora conditions were not observed to

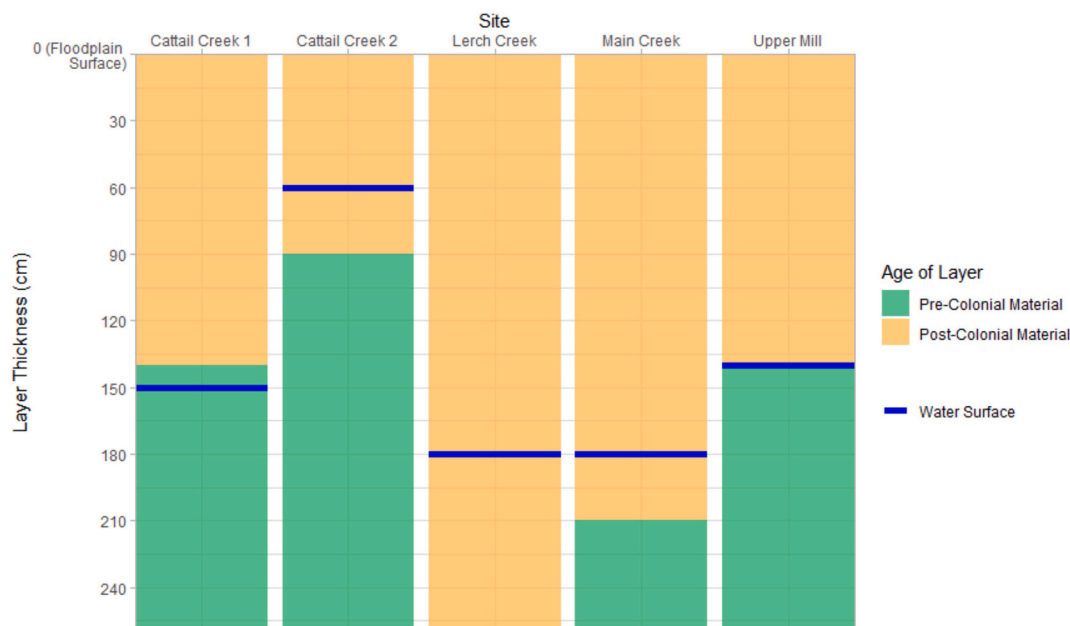


Fig. 3. Approximate depths of pre-colonial soils at four sites visited during reconnaissance across the county. Two separate samples were taken at upstream and downstream portions of Cattail Creek (Cattail Creek 1 and 2 respectively).

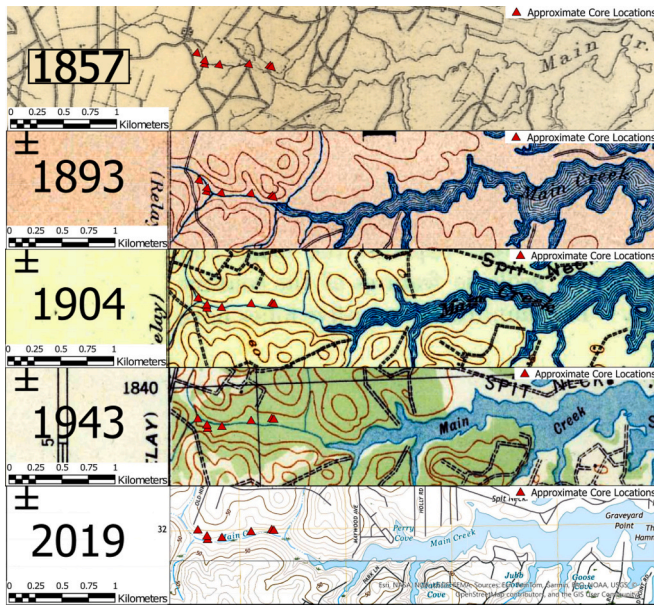


Fig. 4. US Coast Survey and USGS historical topoquads showing the nontidal Main Creek headwaters and study area and open-water tidal embayment from 1857 to 2019. A possible retreat of open water and expansion of land at the headwaters may be seen, particularly in the earlier periods. Despite uncertainties in earlier mapping products, open water does extend beyond a tributary that drains from the north, which by 1904 clearly drains into confined portions of the river. This is one potential line of evidence, along with results from core and geophysical exploration, of postcolonial settlement potentially leading to progradation and retreat of open water. Main Creek flows from left to right.

be static, however; pollen concentrations from *Alnus*, *Quercus*, and other woody taxa were observed to change in general proportion inversely related to fern populations, with evidence suggesting some of these shifts are tied to changing depositional patterns as observed in the lithology (Fig. 6). Understory vegetation populations such as ferns were also observed to shift in composition shortly before the CH (Fig. 6).

The CH tended to overlap with a transitional pollen community distinct but related to the precolonial community, which generally

showed a gradual transition from precolonial to postcolonial species, but also elevated *Osmunda* fern and *Nyssa* in some cores (Fig. 6). Postcolonial sediments also typically exhibited the following patterns, including: (1) a lens of fine to medium sand immediately beneath pollen changes associated with the CH in many cores; (2) a gradual decline in *Alnus*, fern, *Quercus*, and total woody populations before stabilizing well below precolonial concentrations; and (3) an increase in *Pinus* and *Poaceae* populations, as well as a substantial increase in pollen indicative of landscape disturbance and agricultural intensification (*Ambrosia*, *Plantago*, *Rumex*, *Zea mays*). Postcolonial soils were slightly redder overall, with over 90 % of postcolonial soils with color hues of 10YR, and with moderately greater/lighter values and moderately greater chroma, with 50 % of soils 10YR 2.5/1, 3/2 and 4/2 (Fig. 5).

Dates in postcolonial sediments ranged from 230 to 120 yrs. BP (mean: ~175 yrs. BP) and place the CH roughly in the early-mid 18th century. Radionuclide dates were occasionally out of chronological sequence (Fig. 6), although within margin of uncertainty, suggesting possible sediment or macrofossil mixing around the CH. Of note is the general rate of sedimentation observed in Core 3R (Fig. 7); only approximately 20 cm of sediments separate macrofossils with radionuclide dates of 890 ± 30 yrs. BP and 730 ± 30 yrs. BP, which is located closely beneath the CH, while 175 cm separated the CH and the surface.

Soil geochemistry also changed in pre- to post-colonial sediments, with notably significant increased concentrations in post-colonial sediments of P (from below detection limit to 2.93 ppm), S (10-fold increase), Co and Ni (8–9 fold increases), V and As (5 and 4-fold increase), and other metals Cr, Zn, Pb, Cu, Fe, Mn, Nb, and Rb (~1–2 fold increases). Concentrations were highly variable, however, with multiple distinct peaks in the stratigraphy.

Linear discriminant analyses discretely classified sediments into both pre-colonial and post-colonial periods using their visible colorspace values (i.e., XYZ, LAB, and greyscale), soil geochemistry, and magnetism, with effective classification rates of 88 %. This was slightly biased by group – legacy sediment classification accuracy was 92 % while precolonial classification accuracy was 74 %. This was due to misclassification of gray/white-colored sandy lenses which could occur in both precolonial and postcolonial soils. Visible colorspace variables were the most effective classifiers according to the analysis in distinguishing precolonial and postcolonial soils.

3.4.1.2. GPR survey results. GPR data collected at the Main Creek site

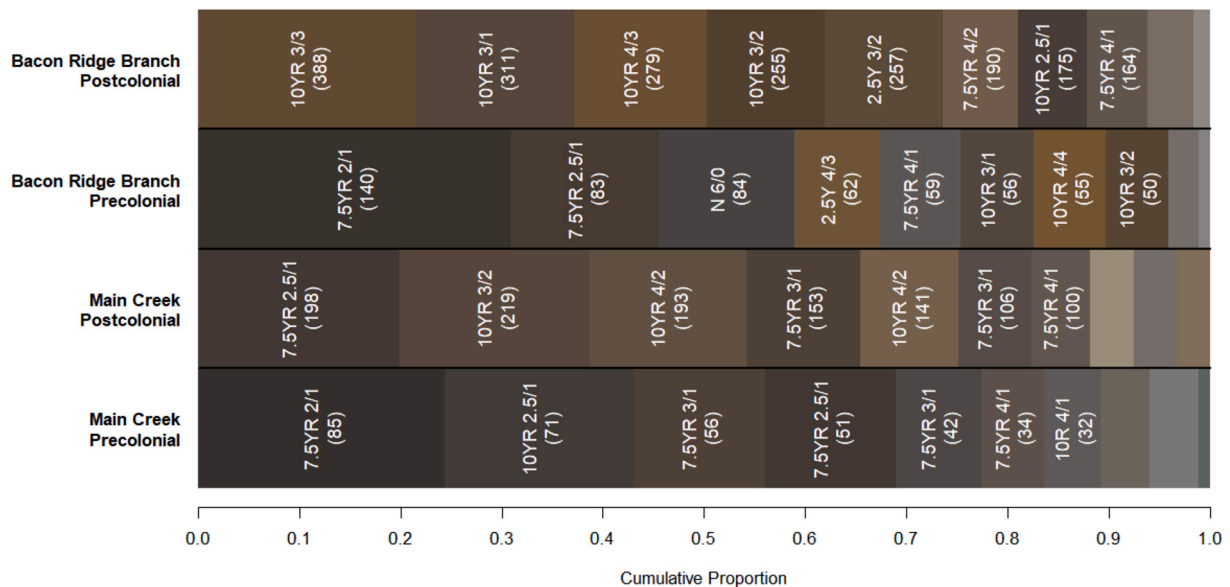


Fig. 5. Cumulative proportion of sediment colors classified by Munsell color occurring in precolonial and postcolonial legacy sediment in the two primary study sites. Number in parentheses adjacent to Munsell color indicates the number of discrete 0.5 cm core segments that fell within that category.

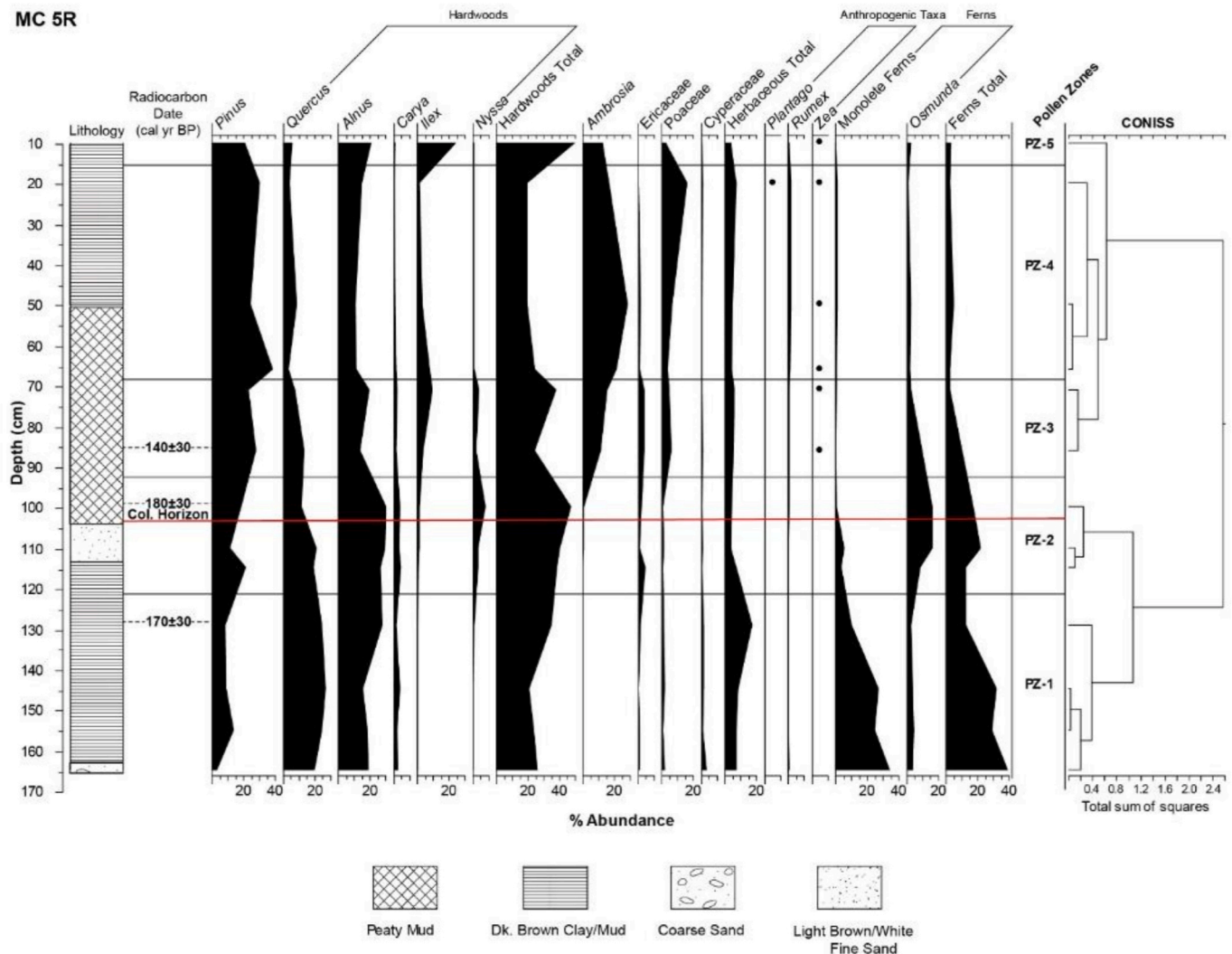


Fig. 6. Depth versus pollen abundance for Main Creek sediment core MC5R, taken near the upper end of the study location, showing radiocarbon dates, lithology, and pollen identifications, with pollen community composition zone clustering results. Colonial horizon marked as a horizontal red solid line was identified by the occurrence and uptick in *Ambrosia* (ragweed) pollen and distinct changes in soil character. Horizontal black lines indicate the boundaries of each pollen zone. Core locations for Main Creek are shown in Fig. 8. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shows poorly sorted, discontinuous soil layers before a loss of signal clarity around two meters below the surface. This is likely the result of the year-round shallow water table, which significantly attenuates penetration depths, and the low elevation differences with the study site to brackish open water (floodplain elevation from 1.25 to 8.5 m NAVD88). Soil velocities ranged between 0.04 and 0.14 m/ns, matching the range of soil textures observed in the core data.

The CH was estimated along GPR transects by pairing the CH depths in the core data with co-located GPR signals (Supplemental Fig. S2). Despite low penetration depths, the CH was visible throughout the study site; the CH was on average one meter below the surface across the valley bottom, and broadly increased in depth as the cross-sectional surveys moved down valley (Fig. 8). In the areas of the study reach downstream of core MC-2R, this resulted in CH depths beneath 0 m NAVD88, corresponding to the CH depths observed at MC-3R. Localized variations in the depth of the CH, and accumulation depth of post-colonial sediment in the valley bottom, was greatest where two tributaries – which have incising headcuts evident in lidar – entered the mainstem valley (Fig. 8). At these locations, geomorphon terrain classifications identified distinct signatures of visible sediment fans in the valley bottom near the mouth of the tributaries, which were also

associated with the locations of the most constrained, incised channels of the main stem river (Supplemental Fig. S3).

The soil layer paired to the CH identified in the cross-valley GPR survey suggest multiple anastomosing precolonial channels. MC-5R shows a predominant main channel with paired side-channels, and similar, if less defined, forms in MC-2R (Fig. 9). The transect at MC-4R, immediately downstream of MC-5R, indicates a potential deeper and wider (~20 m) channel bottom, possibly indicative of a pond or impoundment (Fig. 9).

3.4.2. Bacon Ridge Branch

USGS topoquads dating to 1892, and aligned historical maps to 1860, show the retreat of open water downstream of the study area over the past 150 years (Fig. 10). Multiple *in-situ* stumps were found in the incised, side-tributary at Bacon Ridge Branch, which were identified to *Betula* and *Fraxinus*, the latter of which was dated to 160 ± 30 yrs. BP. Despite the depth of these stumps beneath the modern floodplain (~1.7 m), their dates suggest precolonial sediments were even deeper in the soil stratigraphy.

3.4.2.1. Coring results.

Six cores were successfully recovered for

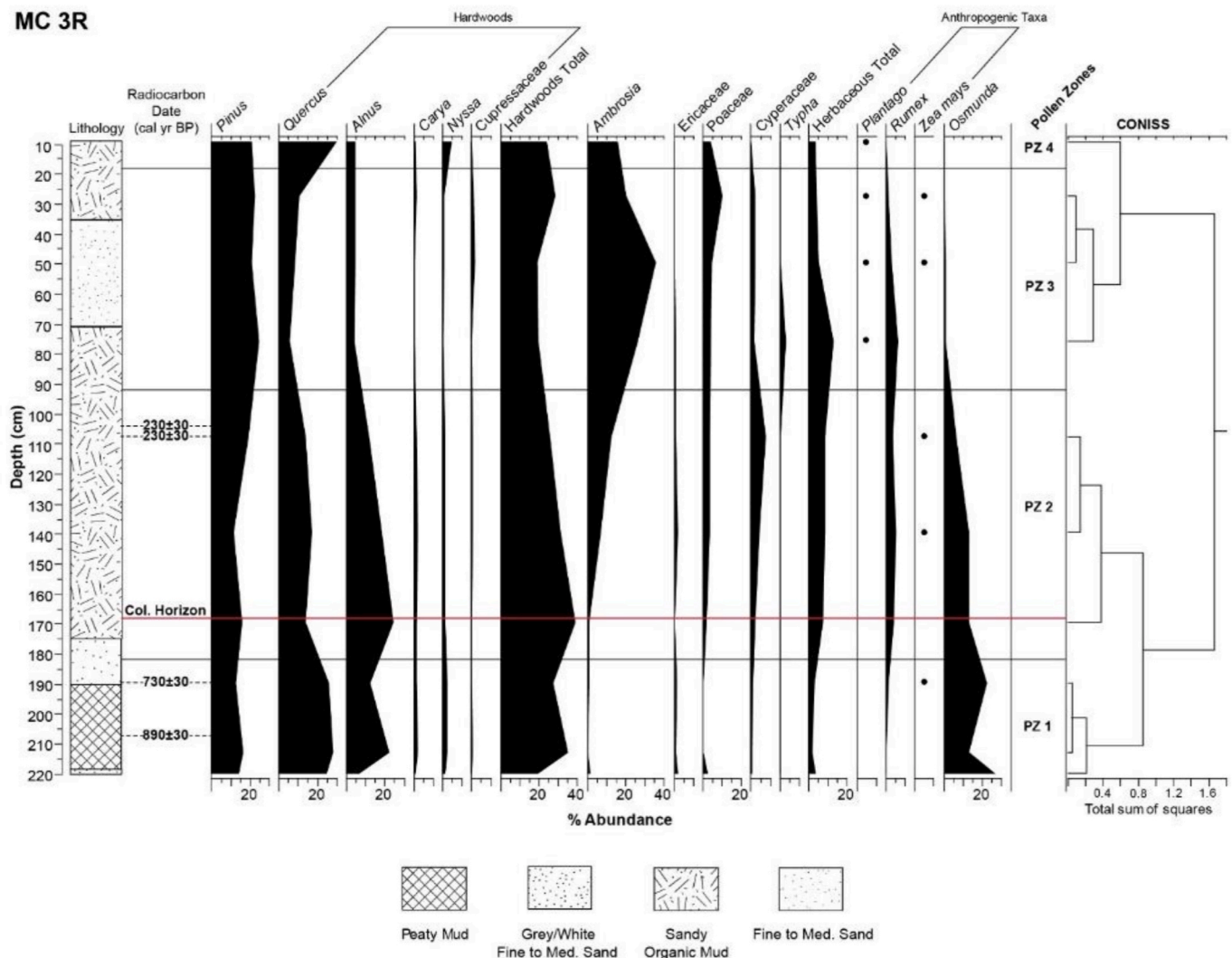


Fig. 7. Depth versus pollen abundance for Main Creek sediment core MC3R, the downstream most core in the 1-km study reach, showing radiocarbon dates, lithology, and changing pollen results through the core, along with pollen community composition zone clustering results. Colonial horizon is marked as a horizontal red solid line and was identified by the occurrence and uptick in *Ambrosia* (ragweed) pollen and distinct changes in soil character. Horizontal black lines indicate the boundaries of each pollen zone. Core locations for Main Creek are shown in Fig. 8. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

analysis, covering saturated floodplain soils in the uppermost areas of the study area, through dry floodplain areas of the incised main channel, and into the lower regions of the valley bottom (Table 1). An additional core was taken from a channel bar within the deeply incised side tributary – the in-channel coring location was selected due to increased recovery potential of sediments beneath the visibly homogenous post-colonial stratigraphy of the high, incised banks (Table 1). Valley bottom elevations at core locations ranged from 1.3 to 5.4 m NAVD88 and penetration depths ranged from 1.19 to 4.80 m. Overall, five of seven core bottoms extended beneath 0 m NAV88, with a maximum bottom depth of nearly 2 m below the NAVD88 datum (Table 1).

Despite some cores penetrating nearly 2.5 m, the CH was only identified in three of the seven cores, and the five most downstream cores recovered only postcolonial sediments (Table 1). The CH, when found at the upstream most locations, was 2.4 m below the valley bottom surface (0.4–0.5 m NAVD88) and was inferred to become deeper in the down-valley direction (e.g., no CH was found through elevations of –0.7 and –1.2 m beneath NAVD88 in downstream cores). Within the side-tributary core, the CH was identified nearly 3.5 m beneath the current valley bottom surface (1.9 m NAVD88; Table 1).

When found, recovered precolonial sediments were predominantly

organic muds, frequently peaty, and with the occasional clay or sandy-clay lens. Precolonial sediments were predominantly dark and low-chroma, with nearly 50 % of precolonial stratigraphy 2.5Y 2/1 or 10YR 2.5/1, and occasional gray lenses, including ~15 % N6/0 (Fig. 5). Precolonial pollen assemblages reflect a landscape dominated primarily by *Quercus* and *Alnus*, with variable minor elements including *Pinus*, *Carya*, Cupressaceae, *Nyssa*, and other woody taxa. Within this, however, precolonial pollen assemblages were highly variable in time (i.e. depth) and space (i.e. among cores). A dynamic understorey of Cyperaceae, fern, and Poaceae alternate dominance over time, with a persistent but minor presence of *Nuphar* (lily) and *Typha* (cattail) indicating some degree of open or ponded water and/or consistently saturated soil conditions (Fig. 11). Charred wood macrofossils were also found in cores, the oldest of which immediately precedes transition to a more Poaceae dominant pollen assemblage (Fig. 11).

Radiocarbon dates obtained in precolonial soils ranged from 4760 yrs. BP (± 30 yrs., ~3.5 m in depth), with multiple samples of varying depths dating to ~6500 yrs. BP, to an earliest date of 8440 yrs. BP (± 30 yrs., ~4.6 m in depth). Dates of 240–250 yrs. BP (± 30 yrs.) were also obtained, although they were within 20 cm of the CH.

Despite inter-core variability, there are several patterns across cores

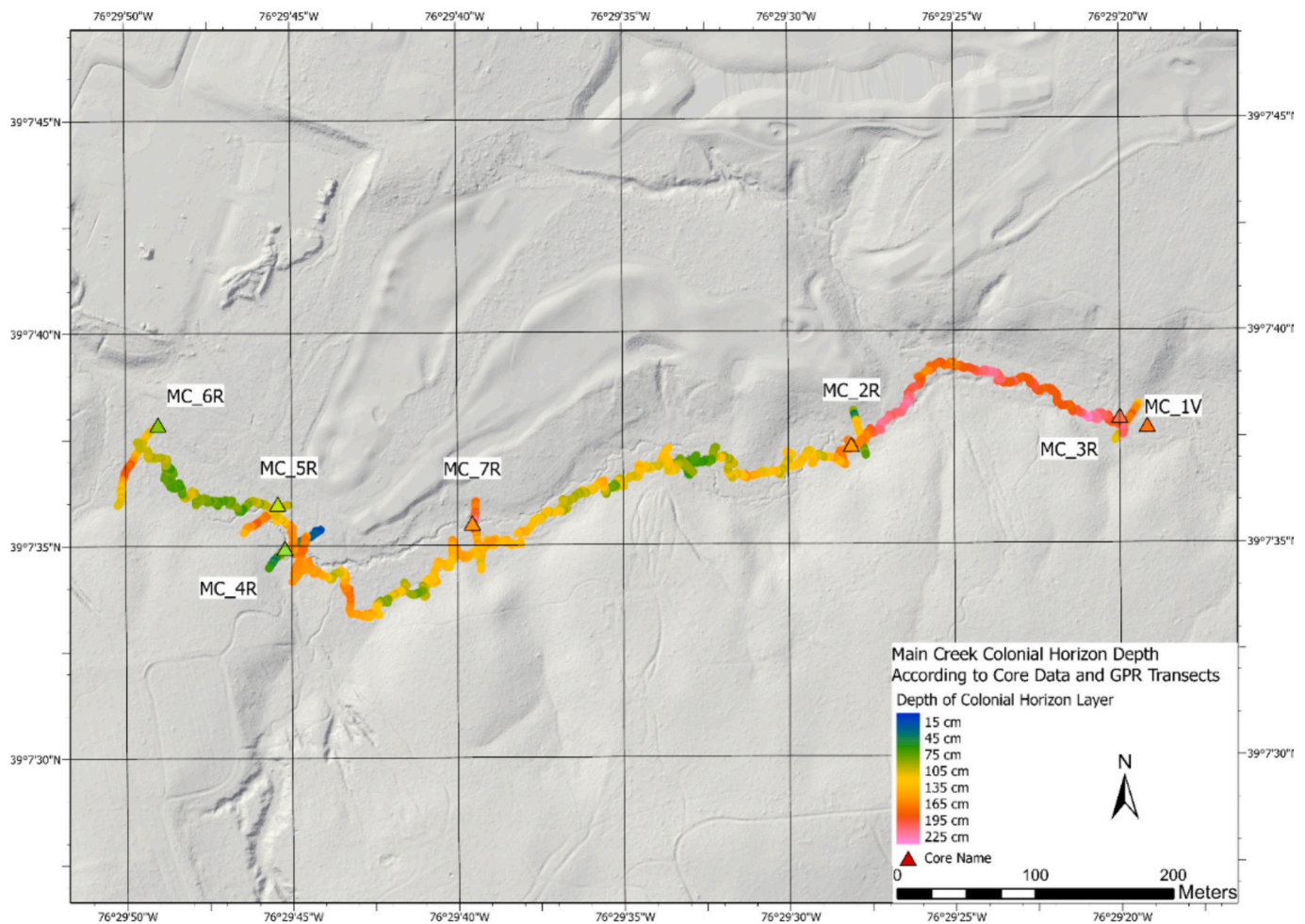


Fig. 8. Depth to Colonial Horizon along Main Creek determined from ground-penetrating radar surveys validated with collocated cores.

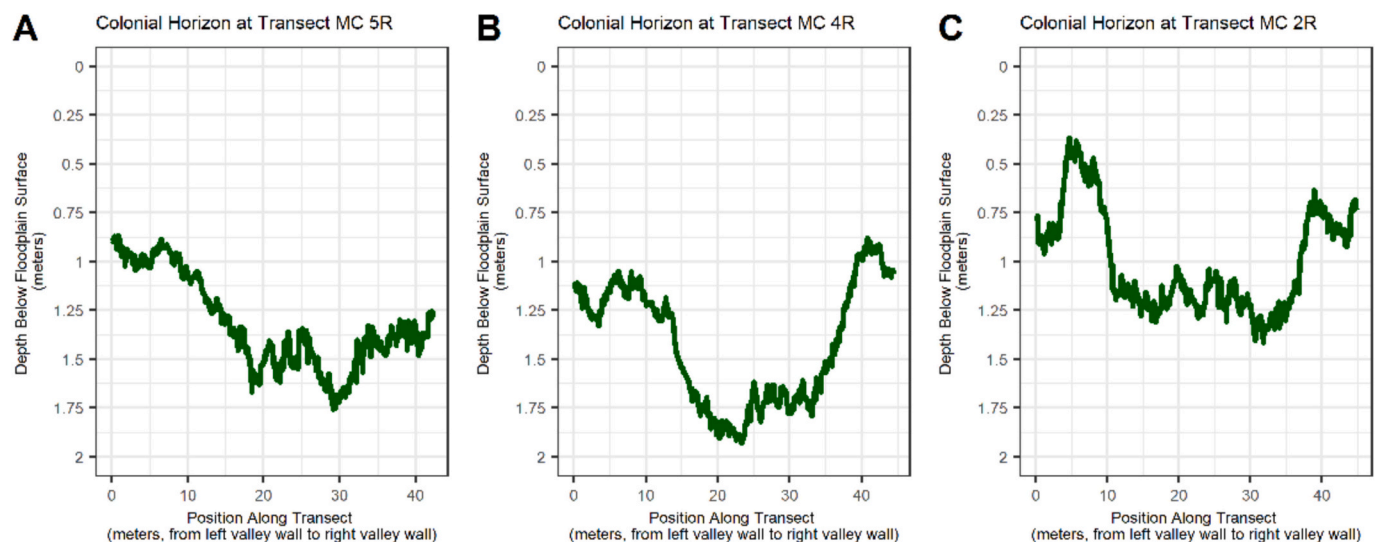


Fig. 9. GPR identified depths of the Colonial Horizon for Main Creek Transects collocated at MC-5R, MC-4R and MC-2R (downstream to upstream). Distance along transects starts from left valley wall to right valley wall. A) Transect 5R shows a main channel and several side channels. B) 4R potentially shows a wide pond-bottom. C) shows multiple low-bank channel forms. Locations of each core may be found in Fig. 13.

with the transition from pre- to postcolonial sediments (Fig. 11). These include: (1) a coarsening of the average grain-size in the local lithology shortly after the CH (± 30 cm), frequently featuring numerous sand

lenses; and (2) an increase in *Pinus* concentration and the appearance and sustained presence of taxa related to landscape disturbance and agricultural practices (*Ambrosia*, *Rumex*, *Plantago*, *Nicotiana*).

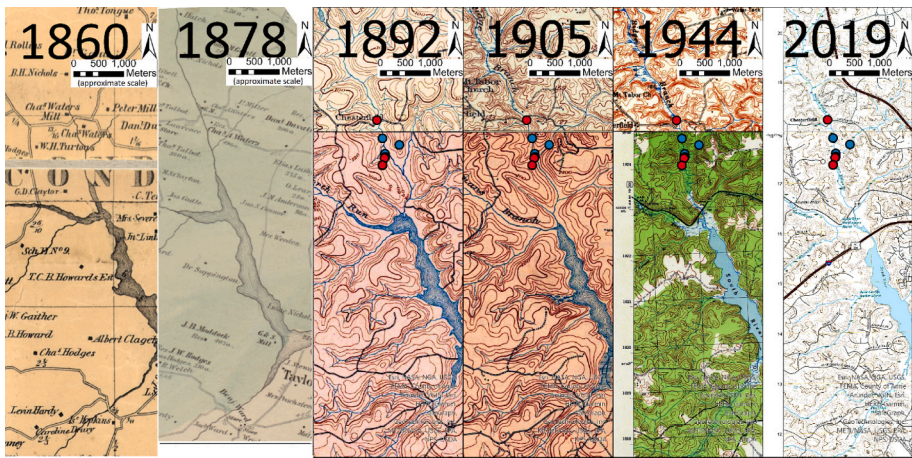


Fig. 10. Historical maps and USGS historical topoquads showing the Bacon Ridge Branch study area and downstream where it joins with the North River, flowing from the west, to create the open water of the South River. A possible retreat of open water and expansion of land for both Bacon Ridge Branch and the North River can be seen. This is one potential line of evidence, along with results from core and geophysical exploration, of postcolonial settlement potentially leading to progradation and retreat of open water.

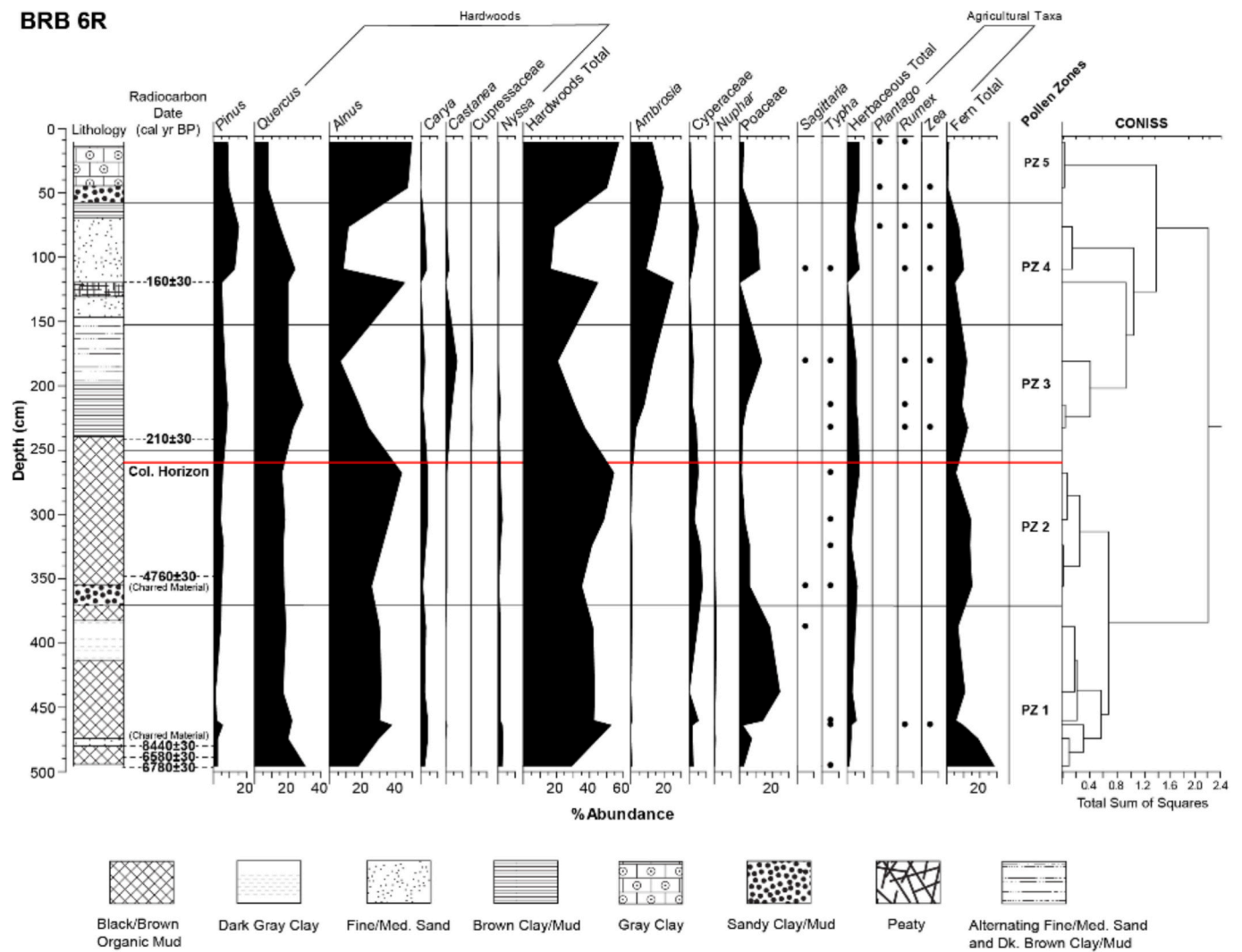


Fig. 11. Depth versus pollen abundance for Bacon Ridge sediment core BRB-6R, the upstream-most and deepest core in the study area, showing radiocarbon dates, lithology, and pollen abundances with depth, along with pollen community composition zone clustering results. Colonial horizon marked as a red horizontal solid line was identified by the occurrence and uptick in *Ambrosia* (ragweed) pollen and distinct changes in soil character. Horizontal black lines indicate the boundaries of each pollen zone. Core locations for Bacon Ridge Branch can be found in Fig. 13. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Postcolonial soils had broadly similar Y and YR hues, but were notably lighter shaded/lower values, with somewhat more chroma, with 50 % of the strata encompassing 10YR 3/3, 10YR 3/2, and 10YR 4/3 (Fig. 5). Depending on the core, postcolonial flora grouped into two to three distinct pollen zones. In the most upstream, deepest core, there is a sharp decline in *Alnus*, with smaller decreases of *Quercus*, Cyperaceae (sedge), and fern, before stabilizing around an *Alnus*/Poaceae -dominant community within the meter closest to the surface (Fig. 11). At other cores, however, we see a series of sudden declines and/or increases in *Alnus* populations, with gradual effects to *Quercus*, ferns, and sedges, before a resurgence of *Pinus* and *Quercus* dominance within a meter of the surface (Fig. 12).

Nine radiocarbon dates in postcolonial sediments were obtained and ranged from 310 to 120 yrs. BP (mean: ~200 yrs.), placing the CH roughly in the late 17th to early-mid 18th century. Radionuclide dates were occasionally out of chronological sequence (Supplemental Fig. S17), suggesting sediment mixing around the CH, although sometimes within measurement error bands. A change in the rate of sediment deposition is also evident, in core BRB-6R, a meter of precolonial sediment is bracketed by radiocarbon dates covering two to four millennia, while in the same core, a meter and a half of postcolonial sediment is

bracketed by dates between 210 yrs. BP (± 30 yrs.) and 160 yrs. BP (± 30 yrs.) alone (Fig. 11).

Soil geochemistry varied in pre- to post-colonial sediments, with notably significant differences including increases of Hg (2.6-fold increase), Sn (1.6-fold increase), Pb (80 % increase), Ni (80 % increase), Fe (70 % increase), Co, Cr, As, Zn (50–70 % increases). Variability was high in core sediments however, with peaks in stratigraphy. In contrast to Main Creek, soil TP decreased in postcolonial sediments to nearly 40 % of the precolonial concentration.

Soils were discretely classified using linear discriminant analyses into both pre-colonial and post-colonial sediments using their visible colorspace values (XYZ, LAB, and greyscale) and soil geochemistry and magnetism, with effective classification rates of 95 %, balanced between groups. Colorspace values were the most effective classifiers for the two groups.

3.4.2.2. GPR survey results. GPR data collected at the Bacon Ridge Branch site shows poorly sorted, discontinuous soil layers before a loss of signal clarity between 1.5 and 2.5 m below the surface. Soil velocities (0.04–0.14 m/ns) matched the range of soil textures observed in the core data.

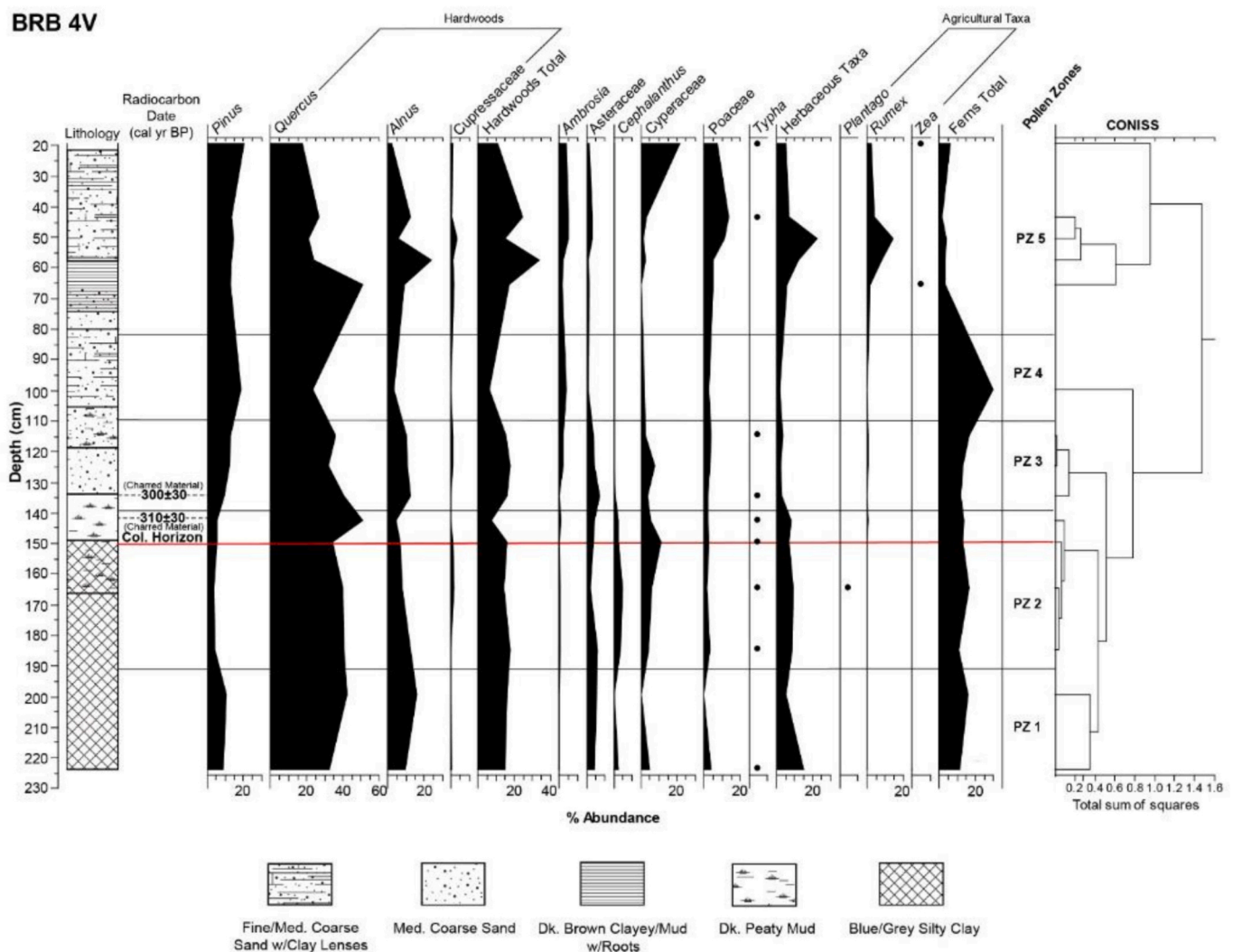


Fig. 12. Depth versus pollen abundance for Bacon Ridge sediment core BRB4V, the core collected from the bed of the incised side tributary in the lower floodplain, showing radiocarbon dates, lithology, and changing pollen results through the core, along with pollen community composition zone clustering results. Colonial horizon is marked as a red horizontal solid line and was identified by the occurrence and uptick in *Ambrosia* (ragweed) pollen and distinct changes in soil character. Radiocarbon dates are indicated at their depths with indicated dates. Horizontal black lines indicate the boundaries of each pollen zone. Core locations for Bacon Ridge Branch can be found in Fig. 13. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The cores indicate that the CHs, even when recovered, were on the edge of the detection range available for the GPR-unit and antenna used. Depth of detection was limited due to the high soil moisture and high-water table of the site relative to unexpected depths of the CH. When the CH was detected at GPR transects, this was typically at relatively shallower depths near the valley wall, and the CH increased in depth beyond GPR detection limits towards the middle of transects (Fig. 14). The GPR data did capture additional shallower stratigraphy which suggest some postcolonial channel evolution at Bacon Ridge Branch

(Fig. 13), with subsequent layers showing fill and later areas of incised erosion.

In addition, deep hyperbolas were observed in the GPR data for nearly every transect collected on the main stem of Bacon Ridge Branch (e.g., Fig. 15). These hyperbolas were clearly distinguishable from soil layers by their distinct curvature and ranged in depths from two to three meters below the surface, and with many at the edge of detection. Hyperbolas of this nature are commonly observed in ground-penetrating radar data when observing buried hard features such as pipes, stones,

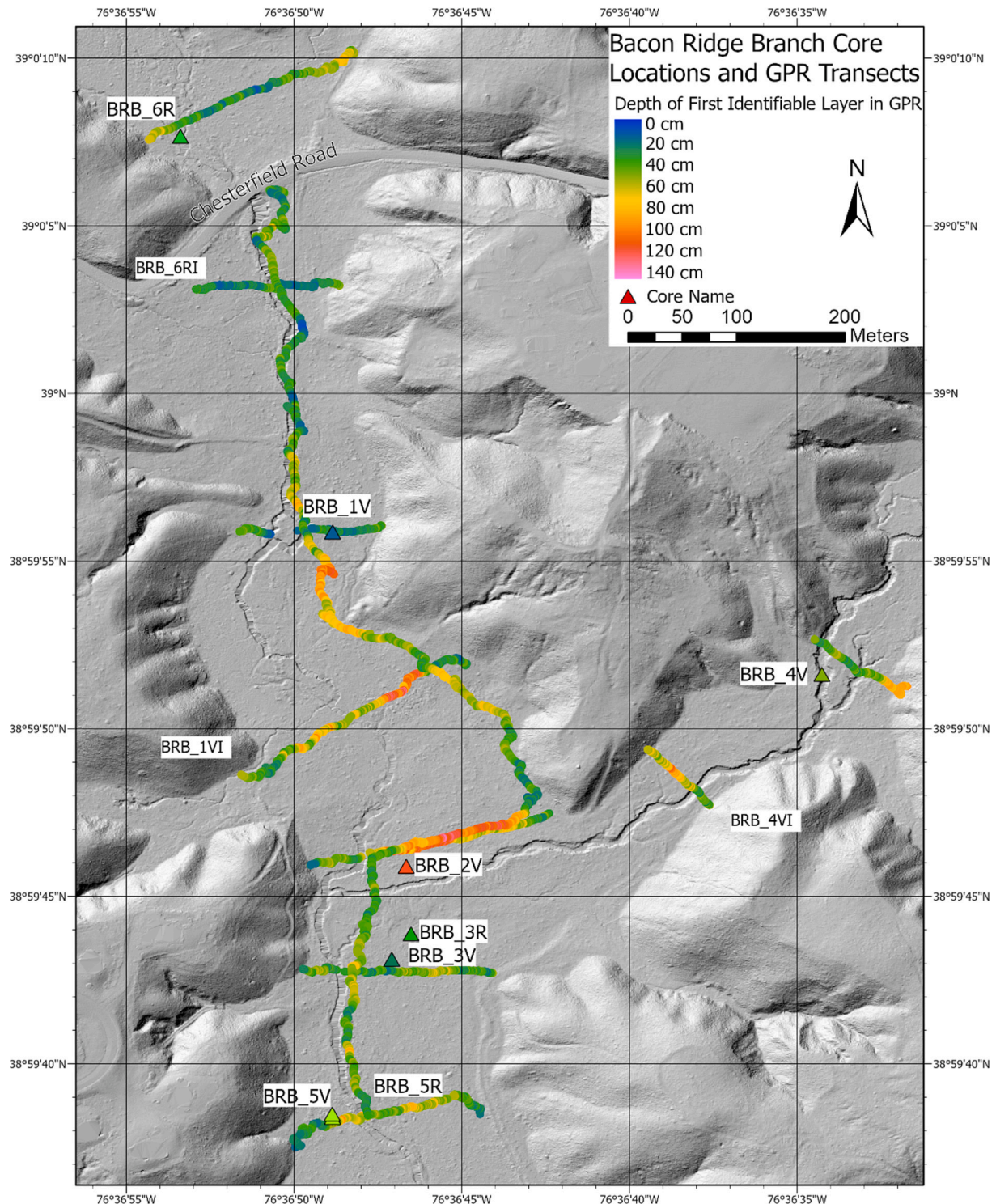


Fig. 13. Map of the depth to first distinguishable sediment layer in Bacon Ridge Branch as determined from the ground-penetrating radar surveys validated against collocated cores.

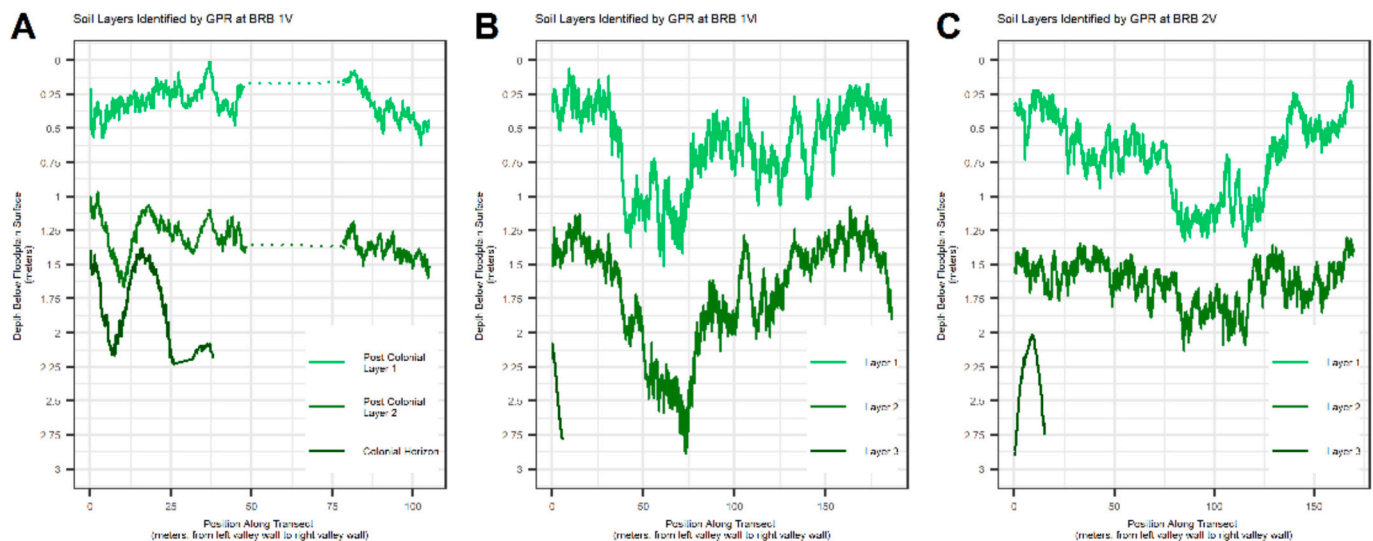


Fig. 14. GPR identified depths of the Colonial Horizons in Bacon Ridge Branch Transects collocated at BRB-1 V, below 1 V (i.e., 1VI), and 2 V. A) Transect 1 V identified the colonial horizon near left valley wall, but lost signal below detection depth of the GPR at that transect. Dotted lines in postcolonial layers 1 and 2 were due to missing data in deep channel and accessibility in a mid-channel island. B) Postcolonial Layer 1 and 2 show an incised main single channel. C) Postcolonial layer 2 shows general aggraded and no clear channel form. Postcolonial layer 1 shows formation of main channel, with potential island or side channel. All distances along transects start from left valley wall to right valley wall.

or logs. We found no evidence suggesting pipes or similar conduits were buried in the study area, and their stochastic distribution longitudinally and vertically suggests these are likely evidence of depositions of large wood arranged throughout the valley bottom. The vertex of the deepest-most hyperbolas aligned approximately (± 0.5 m) with the CH for transects near where precolonial soils were recovered.

4. Discussion

Our study employed a multi-scale, weight-of-evidence approach that integrated data from multiple sources and field-based explorations to investigate the potential legacy changes – and precolonial conditions – of the hydrology, geomorphology, and ecology of river corridors within the Mid-Atlantic Coastal Plain of the USA.

Across the various scales and data sources examined within this study, our findings include: 1) evidence that precolonial stream corridors could be characterized as wooded, scrub swamps and with increased occurrence of bog conditions; 2) a spatially and temporally dynamic patch mosaic ecosystem, induced by natural disturbances such as beaver and fire; 3) substantial amounts of postcolonial legacy changes, including burial of precolonial sediments so that they were typically not visible in modern streambanks; and 4) evidence of land progradation into estuarine areas, even in small Coastal Plain watersheds.

Together, these findings provide important contrasts with existing paleo-studies of river corridors conducted in the Piedmont physiographic province and used in recent restoration designs. Notably, our findings suggest an alternative wooded stream reference state for the Coastal Plain that differs from prior descriptions of paleochannels in the Piedmont. These differences are relevant for informing restoration designs and management approaches within the Coastal Plain.

4.1. Buried precolonial wooded swamps and bogs

Precolonial sediments were buried in valley bottoms to an extent that precolonial soil horizons were not visible, even in highly incised streambanks. Precolonial strata were dark, peaty, organic rich sediments clearly distinguishable by color from the more sandy, less organic postcolonial sediments. Precolonial sediments contained pollen assemblages reflecting both the local (stream corridor, valley bottom) and

regional (sideslopes, upland terrace) vegetation. The riparian vegetation community within the stream corridor was largely dominated by *Alnus* (alder), indicative of *Alnus* shrub swamps, which can be found in some Coastal Plain floodplains in the present day (Tiner and Burke, 1995). Alders are rapidly growing shrubs that tolerate well-drained, yet saturated soils, and can grow into dense thickets up to 20' high (>1 m in height within their first year). Other woody trees and shrubs tolerant of saturated, soggy soils were also variably present in smaller numbers, including *Acer*, *Carya*, *Nyssa*, and *Betula*. Ferns were abundant, and herbaceous taxa included Poaceae, Cyperaceae and other water tolerant taxa including *Typha* and *Nuphar*. Overall, precolonial taxa indicate wet, hydrologically connected, and frequently inundated swamp river corridors.

Sphagnum moss and Ericaceae heath, indicative of bog-like ecosystems, were also found in the precolonial soils at one of our two focus sites and in multiple other sites examined across the county (two of four regional sites for *Sphagnum*, three of four regional sites for *Ericaceae*). While modern bogs are present elsewhere in the county – including in an adjacent watershed to our focal site where we found buried bog taxa – these are rare, and under active protection and management due to threats from local development. *Alnus*-dominant wetlands with notable *Sphagnum* cover are also noted in several vegetative community types in the Mid-Atlantic and can be associated with beaver activity (Fike, 1999). Our study suggests that acidic bog conditions were likely much more common throughout the region prior to historical disturbances and postcolonial legacy sediment burial.

The occurrence of agricultural taxa in precolonial sediments, namely *Zea mays*, also indicates the presence of pre-Columbian agriculture. However, these taxa were rare in occurrence and not coincident with other indicators of land disturbance, such as *Ambrosia* pollen, nor sedimentological indicators of rapid sediment accumulation. This provides additional evidence that precolonial agricultural practices, though present, were not highly disruptive geomorphically, as suggested by James (2011).

4.2. Spatially and temporally dynamic patch mosaic

Importantly, our results demonstrate that these precolonial ecosystems were not static in time or space but were spatially and temporally dynamic ecosystems best described by Wohl et al. as “kaleidoscope

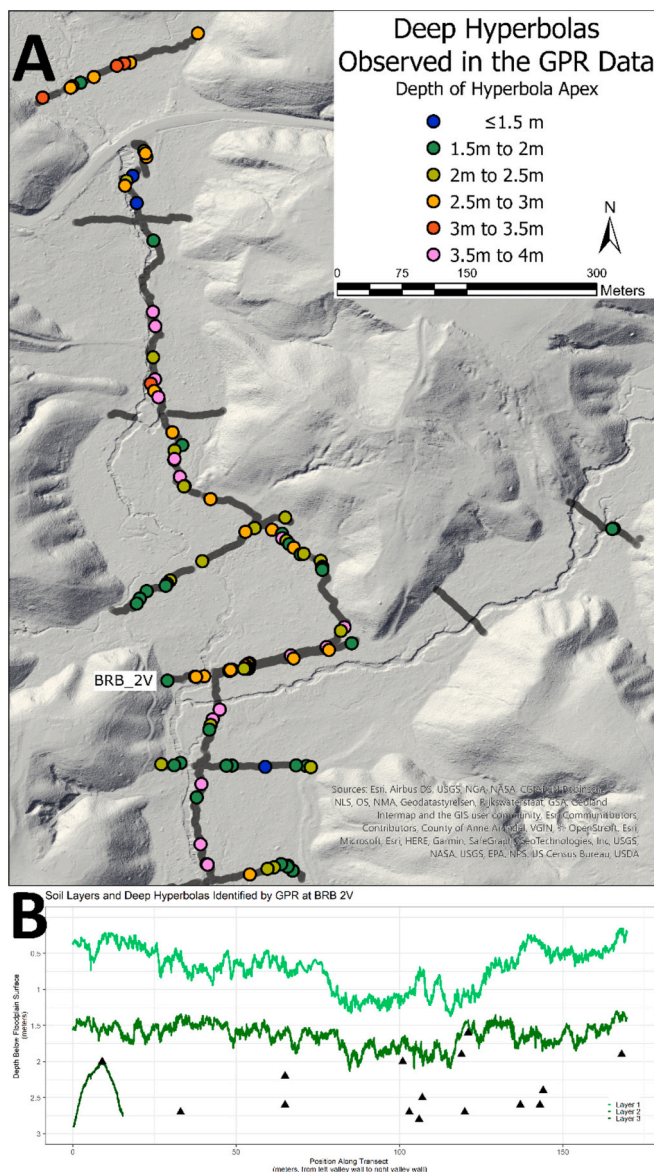


Fig. 15. A - Map of the deep hyperbolas found in the Bacon Ridge Branch GPR data along GPR survey transects (gray lines). B - An example of hyperbola locations represented in GPR transect relative to post-colonial stratigraphic layers are provided at cross-section BRB 2 V, where the apexes of the deep hyperbolas are represented by a black triangle, and the whole hyperbola trace is provided for the left-most hyperbola. Other hyperbolas only have vertices indicated for clarity. Apex of the hyperbolas indicate a buried object, interpreted here to be buried wood.

ivers" (Wohl et al., 2021). Kaleidoscope rivers contain a patch mosaic of different geomorphic forms and vegetative succession, and are driven by various geologic, biotic, and geomorphic processes. Notably, heterogeneous corridors exhibit frequent changes in channel positioning and vegetative dynamics.

Our data suggest the occurrence of multiple planforms, with geophysical exploration providing evidence for single threaded forms, ponded areas, and multi-threaded areas. The occurrence of occasional homogenous, gray sandy lenses present in precolonial stratigraphy also indicates the occurrence of channelized flows. The geophysical detection of numerous precolonial large wood accumulations also suggests a strong influence of vegetation on overall dynamic channel planform and avulsion formation (Gurnell, 2013). Together, Coastal Plain river corridors, although now largely incised single threaded channels, may have

had diverse precolonial forms of both anastomosing channels and more concentrated single-channel flows, with channel forms highly influenced by biotic, vegetative controls (Castro and Thorne, 2019).

We found evidence of temporal variability by depth within cores suggesting vegetative succession between pond, wetland, meadow, and scrub/wooded habitats. The presence of minimal but frequent *Typha* cattail and *Nuphar* lily indicate extremely wet soils with at least some degree of marsh and open water conditions, while other evidence of Cyperaceae, Poaceae, and *Alnus*-dominant assemblages suggest successional transitions from open water marsh to wet meadow and scrub habitats. We also found different successional vegetation communities among cores – at similar depths and/or dates – indicating spatial patchiness across the corridor.

Consistent with ecological theories of patch dynamics and natural disturbances (Wu and Loucks, 1995), these successional patches were likely driven by localized disturbances from other physical factors (e.g., fire) and biotic ecosystem engineers (e.g., beaver), which helped produce the physically and successional complex ecosystem. While this patch mosaic was locally dynamic, patterns were likely more meta-stable at the valley and river network scale (Wohl et al., 2021). Although exhibiting variability through time, this ecosystem type may have potentially existed for thousands of years, given the range of dates found in precolonial soils (750 yrs. BP – 8000 yrs. BP).

The occurrence of buried char in precolonial sediments, coincident with changes in precolonial vegetation, suggests the influence of fire on this landscape. Specifically, one core indicates a fire-associated vegetation change from a more wooded *Alnus*-scrub dominated ecosystem to one with greater proportion of open-canopied Poaceae (Fig. 11). Our study not only found charcoal radiocarbon-dated to 740 yrs. BP (± 30 yrs.), matching a climatically drier period hypothesized by Brush (1986), but also multiple other pieces of charcoal occurring over millennia. The presence of charcoal corroborates accounts by Besley (1915) who notes that forest fires were historically common in the county and a major cause for concern in the colonial era.

Similarly, we have multiple lines of evidence for the presence and potential influence of beaver on the dynamics of these ecosystems. These include plant pollen assemblages associated with beaver-pond succession, geophysical evidence of wood accumulations, anabranching and pool channel forms, and historical data on beaver's importance in the early colonial history of Anne Arundel County. Although later extirpated, beaver populations were ubiquitous throughout the landscape of eastern North America prior to European colonization (Larsen et al., 2021), with nearly all watersheds able to support beaver to some degree (Naiman et al., 1988). We found that early colonial accounts also corroborate the abundance of beaver in local waterways, through written descriptions (Hawks, 1635), as an instigation of conflict (Jonas, 1966), as a source of funding to the early colonial government in Annapolis (Maryland General Assembly, 1695), and frequency of property names with "Beaver Dam" across the County (Maryland State Archives, 1783).

Beavers prefer to locate ponds in unconfined, wide-valley, low-gradient streams (Polvi and Wohl, 2013), characteristics of both our focal sites and many Coastal Plain streams and smaller rivers. Natural beaver-associated habitats have successional trajectories from beaver pond, into Poaceae/Cyperaceae meadows, and later into *Alnus* swamps (Wright et al., 2002), which corresponds to the dominant pollen signals found in our precolonial sediments. *Alnus* wood is frequently used as beaver forage, preferentially used in dam repair (Northcott, 1971), and is a dominant species in beaver influenced ecosystems across North America (Naiman et al., 1988). Overall, beaver can result in structurally complex valley-bottoms with anabranching channels and abundant logjams (Polvi and Wohl, 2012) and promote side channel development (Larsen et al., 2021), for which we have geophysical evidence for precolonial wood accumulations, anabranching forms, and channelized flows. In addition, beaver dams are much more likely to cause ponding effects – evidence of which we detect as low, intermittent levels of cattail

and lily pollen in the precolonial environment – compared to natural-fall logjams which are typically leaky and with less backwater areas (Polvi and Wohl, 2012). Overall, biotic processes and ecosystem engineers such as beaver are increasingly being recognized as fundamental components of sustaining geomorphic process and form (Castro and Thorne, 2019; Polvi and Wohl, 2013), and given historical weight-of-evidence, should not be overlooked in evaluating historical geomorphic processes.

4.3. Substantial postcolonial changes

We found significant volumes of postcolonial legacy sediment accumulated within valley bottoms across the county, burying the precolonial environment and hiding from view the magnitude of changes. Even *in situ* tree stumps exposed within modern river beds – which were found throughout the region and suggest a buried historical valley bottom – were found to emerge from subsequently buried postcolonial floodplains, contrary to our expectations. Postcolonial sediments were on average coarser, lighter in color, less organic, frequently enriched by metals, and were deposited extremely rapidly. Pollen communities indicated diminished floodplain connectivity and generally drier floodplain soils, although with a high degree in variability, likely related to different disturbances throughout the county. Although many streams were incised, we found that streams generally remain perched within postcolonial legacy sediment and have not eroded back to their historical baselevels.

Postcolonial sediments show an increase in *Ambrosia*, along with *Pinus* and *Poaceae*, and other anthropogenic and agricultural taxa. *Alnus*, *Quercus*, and total number of woody taxa also decline in the pollen record, as do ferns and sedges, and *Ericaceae* when they occurred. The changing pollen assemblages matches Elliott and Brush (2006) who also found a rise in *Ambrosia* and decline in *Quercus*, *Alnus*, and other taxa above a CH approximately a meter below the surface elsewhere in Anne Arundel County.

Postcolonial disturbance, indicated by the CH, first occurred at our focused sites between the late 17th century and early/mid-18th century. Our estimate of initial postcolonial disturbance is slightly later than Elliott and Brush (2006), who estimated an initial land clearance date of approximately 1650 CE in another watershed within Anne Arundel County. Early colonial disturbances were likely spatially variable with settlement patterns, and initial disturbances may have first been more limited, suggested by the initial occurrence of *Ambrosia* pollen at low concentrations before later increases in many cores, and the presence of statistically distinct transitional pollen-zones. Signals of land disturbance increased through time in our cores, likely reflecting transitions in agricultural practices, population increases, and increased land clearance. Agricultural practices transitioned from initial hoe and mound agriculture to more erosion-prone plow tilling in the mid to late 18th century (Miller, 1986). Deforestation for agricultural uses and timber in shipbuilding also increased; Besley (1915) notes that the county's deforestation peaked in the mid-1800s to only ~20 % forest cover, down from ~95 % forest cover before colonization (Brush, 1986). Deforestation was not uniformly distributed; the northern parts of the county were clearcut, while the southern parts of the county were preferentially culled for the best timber. This is also apparent in our pollen record: the loss of woody taxa at Main Creek (northern Anne Arundel County) was more sudden and severe than the loss of woody taxa at Bacon Ridge Branch (central Anne Arundel County).

Overall, however, our cores indicate it took decades to centuries to deposit material that previously took millennia, which also matches increased postcolonial sedimentation rates found in the southeastern Coastal Plain (Jones et al., 2017). GPR surveys of Bacon Ridge Branch also captured changing channel and valley bottom topography during this period as channels evolved to deal with elevated sediment loads. During this postcolonial period of high sediment yields and aggradation, these stream corridors likely were in a process state of low biotic controls and low erosion resistance, leading to high bank and channel

instability (Castro and Thorne, 2019), even as they were largely depositional.

More recently, and near the top of the cores, there has been a return of some woody taxa such as *Alnus* and *Quercus*, at times returning to precolonial levels, reflecting recent-era patterns of reforestation (Brush, 2009), a phenomenon also seen in other Coastal Plain cores (Jones et al., 2017). However, understory elements common in pre-colonial soils (e.g., ferns or sedges) remain at negligible numbers, and have been replaced by *Poaceae* and *Ambrosia* at large, perhaps reflecting diminished floodplain connectivity and generally drier floodplain soils indicated by changes in plant community preferences.

As sediment supply likely decreased after the main postcolonial soil disturbance subsided, a phenomenon observed in adjacent physiographic provinces (Wolman, 1967), many channel forms would have incised into their current predominantly single-threaded form (Harvey, 2006). As excessive sediment supply decreased and extreme rates of annual floodplain deposition decreased, vegetation was likely able to reestablish and would provide more controls on channel form and evolution (Castro and Thorne, 2019).

Soil geochemistry identified a suite of postcolonial metal enrichments, including mercury, lead, nickel, iron, tin, cobalt, chromium, arsenic, and zinc. Copper mining near Baltimore dates to as early as 1722, with Maryland being documented as an important early copper-producing state in the latter part of the 18th century and again in the 1830s and 1840s (Pearre, 1964). Early chromite mining also occurred in the Baltimore region during the 1820–1880s (Bain, 2005). Local mines also produced lead, zinc, cobalt, nickel, and iron (Pearre, 1964). Although mining was located predominantly in the more inland Piedmont and Ridge and Valley physiographic provinces, smelting sometimes occurred closer to coastal ports, with notable smelting furnaces occurring on the banks of the Patapsco River on the border with Anne Arundel County (Pearre, 1964). As a result, atmospheric deposition from smelting may account for enrichment of metals in these Coastal Plain postcolonial sediments. However, within-core variability in metal concentrations was high, indicative of more distinct pulses of metal inputs. Overall, distinct color changes associated with organic matter was a more reliable and better primary discriminant of pre- or postcolonial sediment classification.

Lastly, other studies have debated the necessity and relative importance of milldams in creating legacy sediment deposits (Donovan et al., 2015; Hupp et al., 2013; Noe et al., 2020; Pizzuto et al., 2024; Walter and Merritts, 2008). We found that, despite our study area's location in the relatively low-gradient Coastal Plain, milldams were common throughout the region. In the field, we found that milldams were often associated with incised channels and large accumulations of legacy sediment in the historical impoundment. However, we found legacy sediment deposits to be ubiquitous throughout the landscape, regardless of the presence of a dam. The low-gradient context and coastal nature of Coastal Plain streams, especially as channels approach tidewater, likely induced legacy sediment deposition and trapping, resulting in substantial legacy sediment deposits, regardless of the presence of mill dams. Therefore, we conclude that mill dams were not required for legacy sediment to affect modern channel forms in the Coastal Plain.

4.4. Postcolonial land progradation

We found evidence that the sheer volume of postcolonial sediment caused localized land progradation into the estuary zones of the Chesapeake Bay. Historical maps, sediment cores, and geophysical surveys indicate a change from open water to land, with the CH now lying well below the modern waterline in notable portions of our focused sites. As a result, the accumulations of meters of legacy sediment have effectively raised portions of the landscape above the water level, while further terrestrializing other low-elevation areas, a phenomenon that has been reported in other nearby small drainages to the Chesapeake Bay (Pasternack et al., 2001).

At the focused site of Bacon Ridge Branch, analysis of our sediment core and geophysical exploration suggest that postcolonial sediments accumulations extend to depths beneath 0 m NAVD88 for much of the 1 km long study area, with localized exceptions nearer to the valley margin. Despite the study area ranging 1 to 2 km upstream of the river mouth, these data suggest much of the valley bottom might have been open water or tidal marsh prior to colonial disturbance, possibly terminating near the historical Chesterfield Road in our study area. The location of the road and nearby Charles A. Waters mill might have been originally placed to access open waters, as early settlements in the Chesapeake occurred at the head of tidewater to facilitate the transport of goods by boat (Gottschalk, 1945a). A 1769 advertisement for sale of this mill and a related mill on the adjacent tributary of North River describes how the tide comes as far upstream as the mill tail race (Gazette, 1769). While land migration is evident through historical maps and topoquads for the companion mill on the North River, which is now located more than 1 km from open water (Fig. 10; (Marcus and Kearney, 1991)), our study suggests that this migration may have occurred to an even greater magnitude in Bacon Ridge Branch, and seemingly prior to documentation in historical maps (Griffith et al., 1795). Similarly, in Main Creek, even though postcolonial sediment deposits were not as thick, the CH was identified to be 0.5 m beneath NAVD88 at our downstream-most core, and, according to geophysical surveys, beneath 0 m NAVD88 up to ~0.5 km distant from open water today. This also suggests land migration and provides corroborating evidence of migration originally identified in multiple historical map sources. Downstream sediment transport has been noted to stall in head-of-tide areas (Ensign et al., 2015; Noe et al., 2016), and the preferential trapping of transported sediment at head-of-tide, when sufficient to fill channel forms and prevent conveyance, may result in overbank accumulation in local marshes and floodplains and underpin the land migration seen in this study.

Overall, our exploration of legacy sediment depths and elevations at other locations in the county, along with prior studies, suggest that the pattern of open water retreat and land expansion was likely widespread throughout the Mid-Atlantic Coastal Plain. Gottschalk (1945a) estimated an expansion of over 300 ha in coastal land area in the state of Maryland since 1845 due to widespread estuary siltation and land migration. Importantly, the estimate by Gottschalk (1945a) used 1845 as a baseline – due to the start of reliable instrumentation – but which is 100 years or more into the process of colonial disturbance and likely underestimates the true extent of postcolonial land expansion. The historical records document sedimentation problems, loss of navigable ports, and land migration from nearly the earliest points of the colonies (Gottschalk, 1945a; Gottschalk, 1945b). By 1753, the problem was so severe the colonial Maryland government passed an act to mitigate sedimentation and protect navigation on the Patapsco River, the northern border of Anne Arundel County (Maryland General Assembly, 1753). Today, the former colonial deep-water port of Elk Ridge on the Patapsco is ~11 km upstream of navigation and in those areas the river is easily wadable on foot. Similar Acts addressing soil erosion's effects on ship commerce were passed throughout the Mid-Atlantic colonies, often less than fifty years after settling an area (Gottschalk, 1945a; Middleton, 1984). Many other colonial era ports in the region were founded on navigable waters which have either silted in or no longer exist, including Georgetown, District of Columbia; Joppa Town, Maryland; Port Tobacco, Maryland; Bladensburg, Maryland; and Dumfries, Virginia (Gottschalk, 1945a). Yet much of the focus on tidal siltation and land progradation focused on erosion originating from the Piedmont, with erosion and siltation problems in Coastal Plain colonial towns described as 'exceptions' (Gottschalk, 1945a). Instead, our study provides additional evidence of this phenomenon regularly occurring within small watersheds entirely contained within the Coastal Plain region.

While these Coastal Plain channels have incised partly into the formerly deposited postcolonial legacy sediments, downstream progradation of the deltaic wedge have likely altered river controls, with

most streams we examined remaining perched above former baselevels and appearing to be in a state of arrested, incomplete degradation (Cluer and Thorne, 2014). Land migration into coastal waters has fundamentally raised baselevel, lowered gradients, and further limited energy to rework legacy sediment deposits.

Streams affected by dramatic disturbances have been shown to have multiple equilibrium states (Wainwright, 2016) and may not naturally adjust to their previous forms (James, 2018; Renwick, 1992; Schumm, 1973). In particular, the magnitude of legacy sediment disturbances, coastal progradation, and historical beaver extirpation (Correll et al., 2000; Jenkins and Busher, 1979; Johnson et al., 2020; Naiman et al., 1988) suggest a new quasi-steady state for many Coastal Plain corridors which are unlikely to naturally re-adjust back to precolonial forms or elevations. In addition, beaver in mountain streams have been shown to be the driving control between two stable-state channel forms: beavers create anabranching channel planforms with organic, fine-grained ponded sediments, while beaver extirpation results in a single-thread, incised channel with coarser sediments (Polvi and Wohl, 2012; Polvi and Wohl, 2013). While the Coastal Plain is topographically very different than the mountain streams studied by Polvi and Wohl (2013), it stands to reason that beavers may be a driving factor with regard to the channel form exhibited in Coastal Plain river corridors. Urban development and increased overland runoff within the Coastal Plain, on the other hand, has increased erosive energy, but also contributed to local problems with headcut erosion (Palmer et al., 2014). The recent expansion of beaver populations throughout Anne Arundel Coastal Plain (Horton, 2020) may facilitate the recovery of previous channel forms and valley-bottom swamp mosaics, but ones that are formed at new elevations, perched within postcolonial sediments and above original baselevels.

4.5. Limitations

While our study incorporated a nested analysis of different data sources to evaluate precolonial conditions and the extent of legacy changes, important limitations should be considered. While we documented legacy effects at numerous locations across the county, our most thorough field-based data on precolonial stream corridors were restricted to only two locations and supplemented by pollen-based precolonial analysis at four additional sites. While our remote sensing and field reconnaissance surveys provided broader context about the range of watershed conditions across the county, field investigations were necessarily selective. While we aimed to choose sites based on conditions representative of county-wide patterns, the possibility of local variability remains. As a result, we only report on a necessarily limited snapshot of the potential precolonial variability which may have occurred across Anne Arundel County.

In addition, the sheer magnitude of legacy changes at our sites also restricted our ability to reliably obtain information on precolonial conditions. Notably, precolonial sediments were substantially deeper than our initial expectations, resulted in some cores failing to recover precolonial sediments. Similarly, at one of our sites (Bacon Ridge Branch), precolonial sediments were unexpectedly beneath 0 m NAVD88 for much of our study area, and beneath the range of detection for geophysical exploration. However, these unexpected challenges also illustrate the surprising, and notable, findings of our study. The sheer magnitude of legacy changes, even in small Coastal Plain rivers, dramatically reshaped these river corridors, even as they make investigation of precolonial conditions challenging.

Lastly, the scope of our analysis was confined to only a single county, which may limit generalizability of our findings to other areas of the Mid-Atlantic Coastal Plain. Despite these constraints, comparisons with other pollen records recovered from estuarine areas of the Chesapeake Bay (Brush, 1984; Brush, 2001; Pasternack et al., 2001), along with other evidence of coastal progradation in the region (Gottschalk, 1945a; Pasternack et al., 2001), offer support for the generalizability of the

broad findings of our study. However, additional studies of paleoecological conditions in the Mid-Atlantic and other regions of the Atlantic Coastal Plain may provide further evidence for the generalizability of our findings and relevance to other similar landscapes.

4.6. Contrasts to Piedmont studies

Our study examined precolonial stream corridors in the Coastal Plain, a departure from previous studies which focused on the Piedmont and other inland physiographic provinces in the Mid-Atlantic region (Elliott et al., 2013; Pizzuto et al., 2024; Walter and Merritts, 2008). Much like these studies, we found floodplains to contain substantial amount of legacy sediment, eroded during colonial and postcolonial disturbance. While Piedmont postcolonial soils were found to be finer than pre-colonial material (Donovan et al., 2015; Hupp et al., 2013; Merritts et al., 2013; Merritts et al., 2011; Walter and Merritts, 2008), we also found coarse, sandy lenses throughout postcolonial sediments in the Coastal Plain, likely caused by the erosion of Coastal Plain sandy upland soils. However, while Piedmont streams typically have the CH and precolonial sediments regularly exposed, and visible in stream-banks, we found that in the Coastal Plain, the precolonial sediments were typically out of sight and buried below the channel – hiding the full-scope of legacy impacts on the modern river corridor.

The flora and geomorphic form of the precolonial Mid-Atlantic valley bottom described in these previous Piedmont studies have been broadly described as broad tussock-sedge herbaceous stream-wetland complexes (Elliott et al., 2013; Merritts et al., 2013; Walter and Merritts, 2008). This concept has influenced restoration practice throughout the region, which excavate legacy sediments from the floodplain to reconnect riparian areas and create valley-spanning herbaceous stream-wetland complexes (Baltzer et al., 2024; Forshay et al., 2022; Hartranft et al., 2011; Langland et al., 2020; Smith et al., 2020), often at the loss of riparian tree taxa and riparian cover (McMahon et al., 2021).

Our study posits an alternative ecosystem – that many Coastal Plain stream corridors were predominantly wooded scrub swamps (typically *Alnus*), rather than valley-spanning herbaceous wetlands. These scrub swamps ecosystems were a diverse mosaic, however, with successional patches and at the valley-scale could contain open pools with *Typha* (cattail) and *Nuphar* (lily), Cyperaceae meadow, and *Alnus* scrub swamp with understory of ferns, and other hardwoods in the hillslopes. Our findings of a wooded, scrub swamp may function as a reference ecosystem for restoration designs with objectives to retain, rather than remove, riparian cover and rely on riparian woody taxa that are resilient to wet, intermittent flooding conditions.

Although largely overlooked in subsequent discourse and translation into restoration designs, the original Piedmont study by Walter and Merritts (2008) did report some similarity to our findings. They note precolonial wooded swamp wetlands of *Alnus* shrub-scrub with small, shallow anabranching and chain-of-pool streams with frequent over-bank flow (Walter and Merritts, 2008). In addition, Elliott et al. (2013) describes a precolonial *Acer negundo* (box elder) floodplain swamp, but then places this on a spatial continuum of valley position, transitioning from tussock-sedge-rush wetland in the valley bottom, to *Acer negundo* swamp at the valley margin and toeslope, and upland hardwoods on the valley slopes and uplands. Similarly, a recent study in the Piedmont by Pizzuto et al. (2024) also postulates a complex spatial mosaic of valley bottom ecosystems, rather than ubiquitous valley-spanning herbaceous wetlands. We argue that, rather than defined solely by valley-bottom position, we believe these vegetative communities may similarly reflect the spatial and temporal mosaic of different stages of succession driven by localized disturbances, especially beaver, that we describe for the Coastal Plain.

Commentary has suggested that Walter and Merritts (2008) overlooked the role of beaver on the precolonial landscape (Johnson, 2008). Yet initial descriptions by Walter and Merritts (2008) infer these channels were likely heavily impacted by beaver (Walter and Merritts, 2008),

which has been further reinforced and clarified in subsequent writings (Walter and Merritts, 2008; Walter et al., 2008). Our results contribute to this ongoing discussion and emphasize the importance of beaver in the creation and maintenance of this landscape.

4.7. Relevance to restoration

Our results provide important context for the restoration goals and designs applicable to small streams in the Mid-Atlantic Coastal Plain. A principal finding is that restoration designs based on precolonial stream forms described in the Piedmont, particularly those emphasizing herbaceous wetlands, may be inappropriate for use in the Coastal Plain. Instead, we propose a reference ecosystem type characterized by a more wooded, scrub swamp mosaic. Yet the role of the historical reference conditions for contemporary watershed management and stream restoration confronts similar challenges as those initially raised in the Piedmont (Bain et al., 2008; Wilcock, 2008). Numerous publications in the literature have since reflected on the relationship between reference ecosystems and restoration designs (Balaguer et al., 2014; Dufour and Piégay, 2009; Snyder, 2012; Wingard et al., 2017). Notably, this includes the importance of historical fidelity to reference conditions in the context of changing climate and altered watershed conditions, the relevance of fixed ecosystem targets vs process-based objectives, and whether management intervention is justified at all compared to allowing natural processes to unfold.

We suggest that this study may be useful as a guide to future decision-making by resource managers, as described by Wingard et al. (2017), which incorporates the context of altered watershed conditions. Rather than as a fixed-point reference state, our description of the proposed precolonial Coastal Plain swamp mosaic must be understood as a spatially and temporally dynamic landscape, with trends and cycles (Wingard et al., 2017). Specifically, this knowledge can help identify objective based strategies for restoring desirable functional processes associated with reference conditions (Dufour and Piégay, 2009; Wingard et al., 2017). This perspective helps highlight key processes that sustain ecological and geomorphic resilience (Snyder, 2012), including restoration of processes that enables rivers to “restore themselves” (e.g., beaver and/or the restoration of the wood regime; Wohl et al., 2019), and less relies on distinct fidelity to a historical landscape.

In many ways, the recreation of proposed scrub swamp mosaics may be more tractable than the herbaceous wetland designs inspired by the Piedmont, yet it also contains challenges in direct implementation. Notably, the removal of riparian trees during river restoration projects of all types has spurred public resistance (Wheeler, 2023) and prompted updates to state-level guidance to better prioritize and protect riparian areas in restoration projects (Maryland Department of the Environment, 2025). As such, the creation of scrub swamp mosaics may prove less controversial than those necessitating the long-term removal of woody riparian cover for herbaceous valley-spanning wetlands. Yet increased valley bottom inundation even in a more wooded swamp restoration approach would still likely increase mortality of mature tree species initially established on, and adapted to, drier soils. In addition, swamp ecosystems dominated by *Alnus*, a noted nitrogen fixer, may conflict with the regulatory goals to minimize nutrient loadings. Disturbance and shifting habitat mosaics are also key processes of these ecosystems, which may contrast with the desires of restoration projects and regulatory permitting for channels that are relatively fixed and stable (Florsheim et al., 2008). Without disturbance, particularly from beaver, this ecosystem would lack self-sustaining processes and result in vegetative succession to more uniform wooded conditions. Excavation of legacy sediment deposits may also be infeasible in the context of Coastal Plain rivers with substantial coastal legacy sediment deposits and land progradation, and alternative approaches which improve floodplain reconnection to the modern-day floodplain elevation, such as in-channel blockages (Pollock et al., 2014), may be needed.

Management intervention may be required to meet lofty restoration

and regulatory goals identified for the Chesapeake Bay and its watershed. Yet widespread changes to watershed land use may complicate the possibility of whether precolonial river corridor forms and ecosystems are sustainable or desirable in the current context of altered landscapes and associated water quality changes (Dufour and Piégay, 2009). This is particularly relevant to the role of beaver (Bailey et al., 2019), as beaver dam ponds or beaver dam analogue restorations may have different biogeochemical and temperature implications when located in highly-developed, disturbed watersheds (Johnson et al., 2020; Larsen et al., 2021). Beaver-induced changes to channel planforms, increased ponding and localized flooding, and negative perceptions of flooding may also cause resistance from local communities (Warner et al., 2012; Wohl, 2015b). Process-based restoration strategies, such as the use of beaver dam analogues (Pollock et al., 2014), may restore some desirable processes such as increased floodplain inundation in more controlled and deliberate fashion than uncontrolled beaver populations, even if key functional differences remain between beaver dam analogues and actual beaver dam structures (Wohl and Inamdar, 2025).

Yet, the recent resurgence of beaver populations in Anne Arundel County (Horton, 2020) also provides an opportunity for this ecosystem engineer in restoring ecosystems and desirable processes. Our findings support that proactively managing beaver, even in highly urban watersheds (Bailey et al., 2019), may be a deliberate part of watershed management strategies to balance the needs of local communities and desirable ecological services.

5. Summary

The legacy effects of colonial disturbance on Coastal Plain river corridors are simultaneously profound, yet largely hidden from view.

Our study suggests that the pre-settlement river corridor of the Coastal Plain in Anne Arundel County can be best described as a patchy, wooded scrub swamp as far back as the middle Holocene. The river corridor could likely be described as a “kaleidoscope river”, spatially heterogeneous, undergoing various patterns of succession based on various disturbances, including fire and beaver, yet at the landscape-scale maintaining overall metastability over time. Depending on the specific site, the valley sideslopes and uplands would have been composed of *Quercus* and *Pinus*. The river corridor would be largely dominated by patchy scrub swamp of species such as *Alnus*, contain *Nyssa*, *Carya*, and other woody taxa, and also contain beaver-induced ponded areas with *Typha* and *Nuphar*, and successional Cyperaceae (sedge) and Poaceae (grass) meadows. We also found evidence for buried *Sphagnum* and Ericaceae in multiple locations, suggesting rare bog ecosystems were likely more common in the region in the pre-colonial period. Pre-colonial streams would have contained low-bank, complex planform in the valley bottoms, with single-threaded and anabranching sections driven by vegetation and wood accumulations and were likely driven by beaver influences. These floodplains were prone to flooding, depositional, were rich in organics, and attenuated sediment from downstream waters.

Postcolonial disturbance and erosion buried this former river corridor under substantial amounts of postcolonial legacy sediments and resulted in land migration into former open tidal waters even in small drainage watersheds. Even in what are today predominantly wooded basins, we found substantial legacy sediment, river progradation, and altered pollen communities despite disturbances occurring centuries ago – a hidden environmental legacy that persists to this day.

Our results differ from existing precolonial reference conditions described for the Piedmont. While there may be contemporary challenges in the restoration of this ecosystem type in the contemporary landscape, the description of this ecosystem can help identify process-based restoration objectives and inform restoration designs. Put into context with other historical records and documentation of sedimentation elsewhere in the region, our results are likely applicable to similar areas elsewhere in the broader Mid-Atlantic Coastal Plain.

CRedit authorship contribution statement

Matthew J. Cashman: Writing – review & editing, Validation, Resources, Investigation, Data curation, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization, Visualization, Software, Methodology, Formal analysis. **Zach Clifton:** Writing – review & editing, Visualization, Methodology, Investigation, Writing – original draft, Software, Formal analysis. **Bryan Landacre:** Software, Visualization, Data curation, Writing – original draft, Methodology. **Christopher E. Bernhardt:** Conceptualization, Supervision, Validation. **Alex C. Wiedenhoft:** Data curation, Methodology, Writing – review & editing. **Christopher J. Victoria:** Resources, Conceptualization, Project administration, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2025.107771>.

Data availability

All new data collected or derived for this study, including county-wide geomorphic landscape analysis, ecological and dendrochronological data collected during field-based reconnaissance, and ecological, sedimentological, and geochemical results from sediment coring and ground-penetrating radar at the focused intensive field investigations are freely accessible (Clifton et al., 2023).

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