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Evidence of Mid-Holocene (Northgrippian Age) Dry Climate Recorded in Organic Soil Profiles in the Central Appalachian Mountains of the Eastern United States

Mitzy L. Schaney [1,*], James S. Kite [2], Christopher R. Schaney [3] and James A. Thompson [4]

[1] Geography Department, University of Pittsburgh at Johnstown, Krebs Hall 108A, 450 Schoolhouse Road, Johnstown, PA 15904, USA
[2] Department of Geology and Geography, West Virginia University, 330 Brooks Hall, P.O. Box 6300, Morgantown, WV 26506, USA; jkite@wvu.edu
[3] Department of Geography, Geology, Environment and Planning, Indiana University of Pennsylvania, 981 Grant Street, Indiana, PA 15705, USA; cschaney@iup.edu
[4] Division of Plant and Soil Science, West Virginia University, 3115 Agricultural Sciences Building, 1194 Evansdale Drive, Morgantown, WV 26506, USA; james.Thompson@mail.wvu.edu
* Correspondence: m.schaney@pitt.edu

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Abstract: Peatlands in Canaan Valley National Wildlife Refuge hold a pedomemory of Pleistocene and Holocene climatic fluctuations in the central Appalachian Mountains of the eastern United States. A field investigation profiling 88 organic soil profiles, coupled with 52 radiocarbon dates and peat accumulation rates, revealed a distinct sequence of organic soil horizons throughout five study areas. The dominantly anaerobic lower portions of the organic soil profiles consist of varied thicknesses of hemic and sapric soil materials, typically layered as an upper hemic horizon, underlain by a sapric horizon, underlain by another hemic horizon. Peat deposition began after the Last Glacial Maximum with relatively high Heinrich Stadial 1 accumulation rates to form the lowest hemic horizon. Peat accumulated at significantly slower rates as the climate continued to warm in the early Holocene Greenlandian Age. However, between 10,000 and 4200 cal yr BP peat accumulation decreased further and the decomposition of previously deposited peat prevailed, forming the sapric horizon. This interval of greater decomposition indicates a drier climatic with dates spanning the late Greenlandian Age through the Northgrippian Age. The upper hemic horizon within the anaerobic portion of the soil profile formed from high peat accumulation rates during the wetter late Holocene Meghalayan Age.

Keywords: peat stratigraphy; peat humification; Histosols; Canaan Valley; mid-Holocene Climatic Optimum; Appalachian Mountains; pedomemory

1. Introduction

The Laurentide Ice Sheet advanced within 170 to 320 km from Allegheny Mountain peatlands in West Virginia and Maryland during the Heinrich Stadial 2, 26,000 to 23,600 cal yr BP [1–4]. A cold dry climate with alpine tundra occupied this periglacial region of the central Appalachian Mountains during the Last Glacial Maximum (LGM) [5–7]. The climate of the eastern United States, including the Appalachian region, ameliorated to warmer conditions after the LGM, near the end of the late Pleistocene [5,8,9]. The Holocene Epoch, which began 11,700 cal yr BP, is an interglacial with numerous climatic fluctuations in eastern North America [10–13]. The early Holocene Greenlandian Age, defined as 11,700 to 8236 cal yr BP [14–17], was characterized in the eastern United States as a cool and dry period that ended with a pronounced millennial-scale cold event at 8236 cal yr BP [15,18–20]. The mid-Holocene Northgrippian Age, defined as 8236 to 4250 cal yr BP [14–17], was characterized in eastern North America generally as a rise in temperature culminating with the mid-Holocene Climatic Optimum [20–22]. The Northgrippian Age ended with a climatic event at 4250 cal yr BP that manifested in the mid-continent of North America as a widespread and severe drought [16,17,21,23,24]. The late Holocene Meghalayan Age, from 4250 cal yr BP to present [15–17] brought wet conditions to the eastern United States [13].

Climate, primarily temperature and precipitation, is the principal allogenic forcing factor in peatland development over millennial timescales [25–30], with successional vegetation change being a significant autogenic influence [27,31]. Peatlands form when the net primary production of vegetation exceeds decomposition, resulting in the accumulation of organic matter [32]. Peatland persistence requires a positive water balance for long-term growth and maintenance; a positive water balance is generally favored by a higher precipitation [32,33]. Historically, wet climates tend to have greater peat growth rates [34]. Woody peat and *Sphagnum* peat have relatively higher accumulations rates than peat derived from other vegetation types [35]; *Sphagnum* and other bryophyte tissue decompose more slowly than vascular plant litter and roots [36].

Histosols are organic soils comprised of sapric (highly decomposed), hemic (moderately decomposed), and fibric (barely decomposed) materials and are primarily located within peatlands. The acrotelm is the aerobic upper portion of the soil profile and generally consists of less humified fibric soil material that has a lower bulk density. The acrotelm–catotelm boundary is approximately the mean depth of minimum water table during the growing season [37] and is marked by highly humified sapric soil material. The anaerobic catotelm is the lower portion of the organic soil profile and generally consists of various thicknesses of a combination of hemic and sapric soil materials with higher bulk densities. Histosols are in equilibrium with their environment, such that disturbance to the water balance or vegetation community may result in a change in character of the constituent organic soil materials [31,38]. A distinctive feature of Histosols is stratification resulting from the accumulation of plant material under changing environmental conditions [38]. Barber [39] showed a direct correlation of temperature and precipitation to peat stratigraphy, particularly peat humification and the character of the peat. The identification of stratigraphic discontinuities in the degree of peat humification is a frequently utilized tool to assess past climatic and environmental conditions [40]. Peat decomposition and humification are a direct result of peatland surface wetness conditions [29,38,41–43]. Peatland surface wetness relates to the depth from the surface of the water table. Peat decomposition is greater when the peatland surface is relatively dry, when water tables are lower than when the peatland surface is relatively wet [44]. Surface wetness conditions are closely related to climatic fluctuations in precipitation and temperature; thus, peat stratigraphy can act as a proxy climate record [25,29,37,41,45,46].

The analysis of peat stratigraphy and the physical characteristics of the peat have shown that peatlands hold an in situ record of their initiation and subsequent development [47]. Pedomemory is both the capacity of a soil system to record environmental conditions through pedogenesis and the record that is retained within the soil profile [48–50]. Humification is one of the pedogenic processes that determines the pedomemory of peatland development and climatic conditions over time. Histosols may record climate-driven changes in stratigraphy in which drier phases are represented by sapric (highly decomposed) soil material in dark well-humified horizons, and wetter phases are represented by hemic (moderately decomposed) soil material in light less-humified horizons [29,38,42,43].

Using peat stratigraphy, the objectives of this study are to expand and improve the understanding of the paleoclimatic history of five peatlands in Canaan Valley National Wildlife Refuge (CVNWR) and to provide insights into the pedomemory of peatlands in the central Appalachian Mountains. Worldwide, peat stratigraphy has been utilized for over a century to study late Quaternary climate change, but despite the recognized value of peat humification analysis for paleoenvironmental reconstructions [44,51], it has not been used in the central Appalachians. This study adds to existing regional and local peat paleoclimate observations with the characterization of Histosols and peat stratigraphy, revealing the peatland surface wetness dynamics within CVNWR. With 100 soil cores profiled and described, including 30 with lab data, the abundance of observations within this investigation adds breadth to existing regional and local paleoclimate reconstructions. An understanding of past paleoclimate in these peatlands, including how they evolved and responded to climatic change, is valuable knowledge for interpreting how they might respond to projected future climate change.

Project Area

Peatlands commonly occur in boreal regions; however, high elevations along the Allegheny Mountains also sustain local boreal ecosystems [52]. The Allegheny Mountain section of the central Appalachian Mountains [53–56] includes geographic niches that are very similar climatically to more northern boreal peatlands, with a high mean annual precipitation, low mean annual temperature, and low soil temperatures [57–59]. Regional climatic conditions are intensified by orographic precipitation and local topographic frost pockets, where cold, dense nocturnal air drains downslope, decreasing the valley floor temperatures [59].

Allegheny Mountain peatlands range in size from a few to a few hundred hectares [60], and are typically situated at elevations above 730 m in the unglaciated plateau. Byers et al. [61] placed Allegheny Mountain peatlands within the High Allegheny Wetland Ecological System. This system occurs in a southwest–northeast trending ~40 km wide by ~200 km long band along the Allegheny Mountain section of the unglaciated Appalachian Plateaus physiographic province in Pennsylvania, Maryland, and West Virginia in the eastern United States [58]. In general, the Allegheny Mountain section is higher in elevation than the adjacent physiography and is characterized by broad, open structural bedrock folds.

Differential erosion has formed structurally controlled bedrock valleys and concave bottomlands of the Allegheny Mountains. Impeded drainage developed within these valleys before the Holocene [58], most likely by the blockage of drainage by periglacial activity [62]. Allegheny Mountain peatlands occur in or near the headwaters of first- or second-order streams or occur in specific geologic niches [58,60]. Canaan Valley, in Tucker County, West Virginia (Figure 1), is a high-elevation (980 m), breached anticlinal valley, associated with the Blackwater anticline. The headwaters of the Blackwater River, within the Cheat River watershed, drain most of the valley. Resistant Pottsville Sandstone caps the surrounding mountain ridges with elevations of 1250 m. Mauch Chunk Formation siltstones, shales, and immature sandstones form the more easily erodible valley slopes. Greenbrier Limestone and lower Mauch Chunk siltstones and shales underlie most of the valley floor [63–65]. Projecting up to 80 m above the valley floor is a low, elongated ridge comprised of coarse-grained sandstone of the Price Formation exposed along the axis of the anticline [65].

The floor of Canaan Valley contains one of the largest upland freshwater wetland ecosystems of peatlands, marshes, wet meadows, and shrub-forested wetlands in the eastern United States [63]. These are flood- and beaver-influenced wetlands encompassing shrub swamps, sedge fens, wet meadows, and open marshes [61]. Forested swamps occupy the slightly higher elevation around the peatland margins. CVNWR encompasses the northern portion of Canaan Valley, protecting most of West Virginia's largest wetland complex, including five remapped peatlands totaling 246 hectares (Figure 1). Small unnamed tributaries of the Blackwater River, bordered by shallow Entisols with thin histic epipedons or hydric components, separate these five peatlands. These minerotrophic peatlands are characterized by an exceptionally high biodiversity and conservation value; they contain some of the highest concentrations of globally rare plant and animal species within the eastern United States [61]. They have the largest peat deposits located in the unglaciated uplands along the Allegheny structural front in West Virginia, Maryland, and Pennsylvania [57]. They are ecologically classified as very poor fens: very acidic, moderately influenced by ground water, and dominated by sedges, with a continuous carpet of Sphagnum [66]. Bryophyte groundcover vegetation in these peatlands consists of

Sphagnum rubellum, *Sphagnum recurvum*, *Sphagnum palustre*, and *Polytrichum commune*. The herbaceous vegetation includes *Eriophorum virginicum* (tawny cottongrass), *Rhynchospora alba* (white beaksedge), and minor amounts of *Scirpus* sp. (bulrush). Woody shrub vegetation commonly consists of *Photinia melanocarpa* (black chokeberry), *Vaccinium oxycoccos* (small cranberry), *Vaccinium myrtilloides* (velvetleaf blueberry), and *Rubus hispidus* (bristly dewberry).

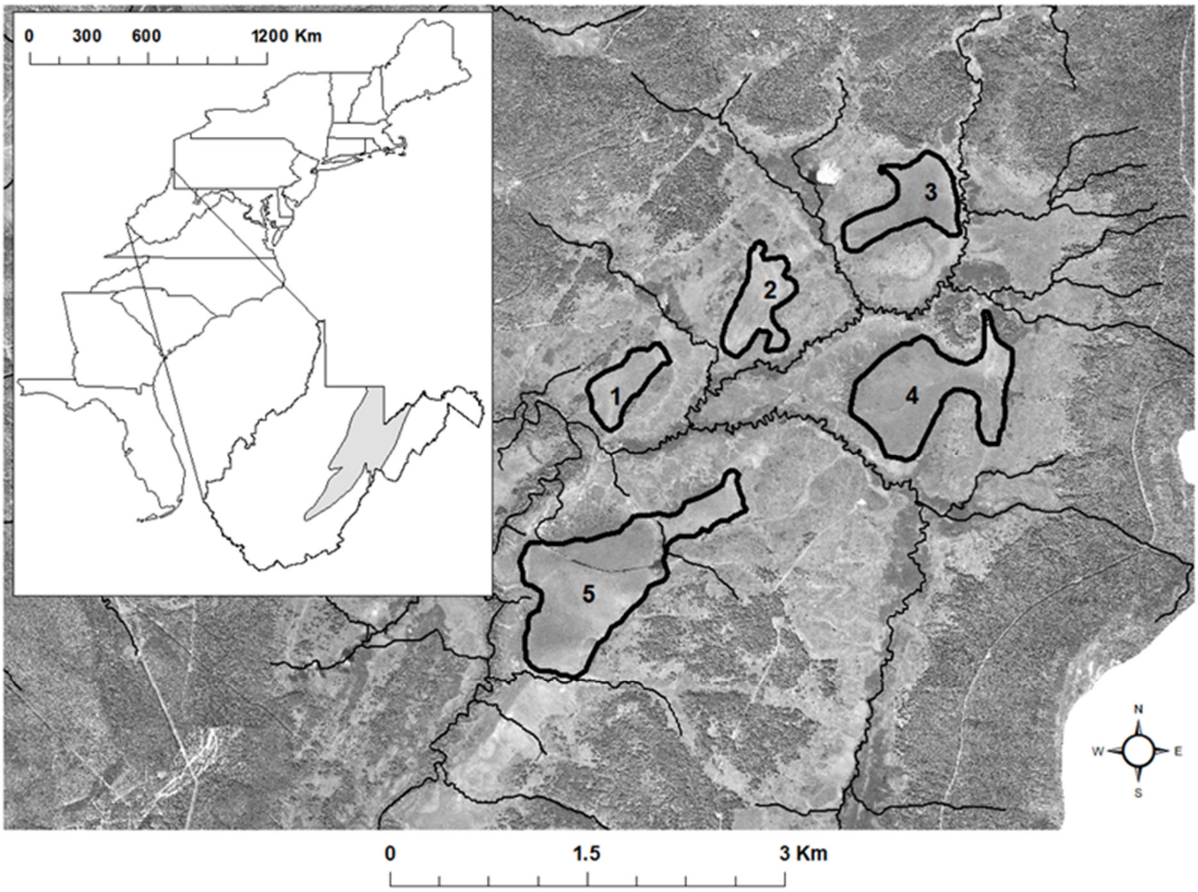

Figure 1. Location of Allegheny Mountain physiographic section (gray polygon) within West Virginia of the eastern United States. Aerial photograph of Canaan Valley National Wildlife Refuge including Peatlands 1 through 5. Aerial imagery obtained from the National Agriculture Inventory Program 2007 by United States Department of Agriculture.

2. Methodology

2.1. Field Methods

Old Soil Conservation Service (SCS) map unit polygons, labeled as "muck and peat", provided an initial base map for this research. The SCS soil polygons were originally published in the Soil Survey of Tucker County [67]; the soil survey data were collected between 1959 and 1964, and mapped on 1956 and 1958 aerial photographs. The five muck and peat polygons were designated as Peatlands 1 through 5 for this study, which included re-mapping these polygons based on new data and updated imagery. Soil morphology was described [68] by profiling 100 soil cores throughout and around the five study areas, including 32 in Peatland 1, 11 in Peatland 2, 19 in Peatland 3, 21 in Peatland 4, and 17 in Peatland 5 (Figure 2). Thirty of the 100 cores were sampled for laboratory analysis, including radiocarbon dating, bulk density, total organic matter content, fiber content, and pyrophosphate color. Soil profiles were classified based on the field descriptions and laboratory data, using the U.S. Department of Agriculture, Natural Resources Conservation Service, and Soil Taxonomy [69].

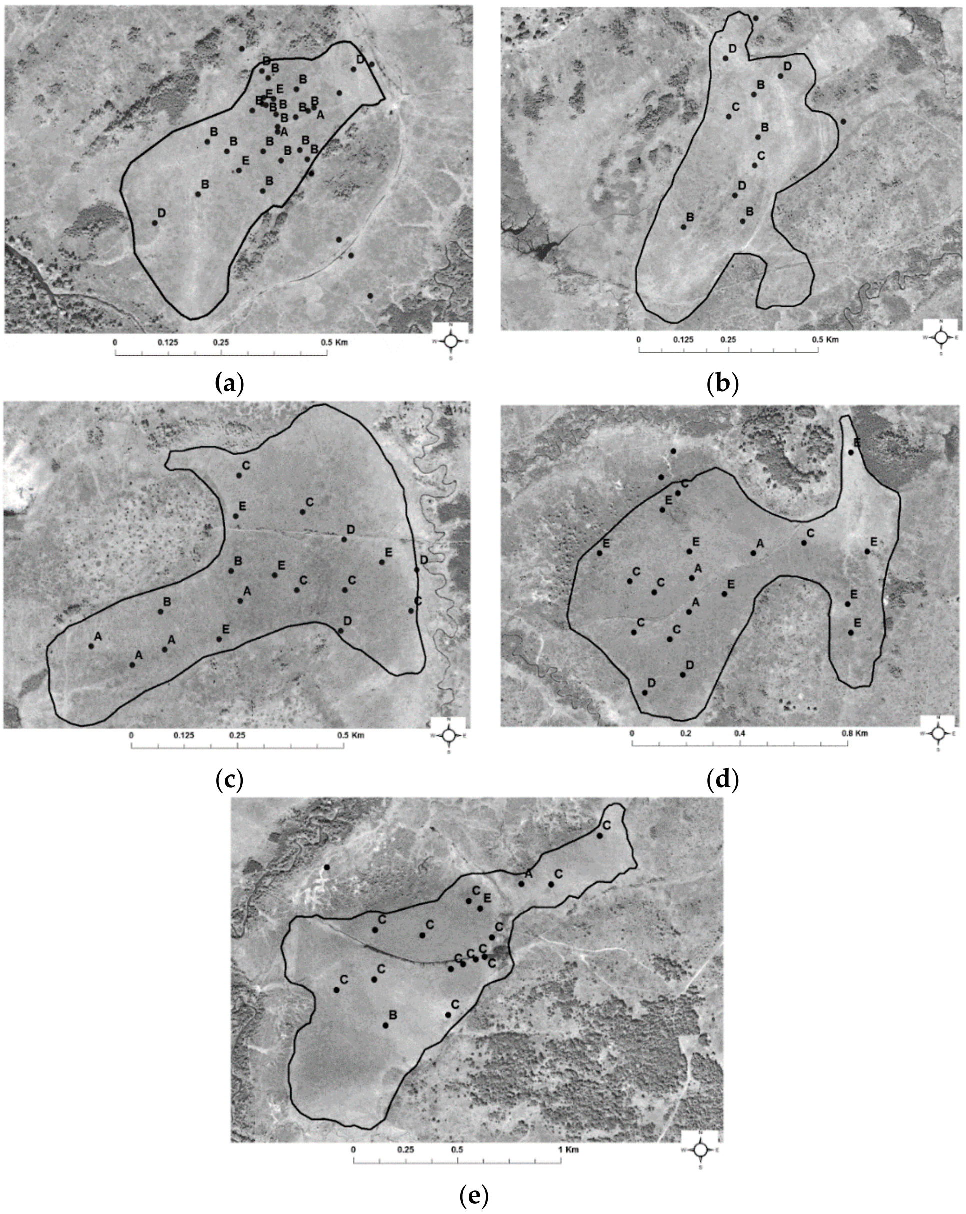

Figure 2. Five CVNWR peatlands with soil cores labeled by categorized catotelm profile type: 2(**a**). Peatland 1, 25 cores, dominated by Type B (SH) profiles; 2(**b**). Peatland 2, 9 cores, with Type D (S) profiles in shallow areas; 2(**c**). Peatland 3, 19 cores, including all five soil types; 2(**d**). Peatland 4, 19 cores, including Type C (HSH) profiles clustered at the thickest peat, surrounded by Type E (HS) profiles, and a cluster of Type A (H) profiles; 2(**e**). Peatland 5, 16 cores, dominated by Type C (HSH) profiles. S and H represent Sapric (highly decomposed) and Hemic (moderately decomposed).

Soil core locations were chosen according to the "free survey" method of sampling soils, which involves the individual development and application of soil–landscape concepts based on the observation that soils vary repetitively and predictably with the geomorphology, topography, and similar information [70]. The locations of cores were representative of the immediately surrounding terrain. Small-scale hummocks and hollows were avoided, as were the locations of known anthropogenic disturbance. Geographic coordinates, location notes, surface vegetation, and geomorphology were recorded for each soil profile location. Excavating and coring equipment varied depending upon the type of material encountered. A shovel was best suited for excavating acrotelm (aerobic zone) horizons, a McCauley peat corer was used to sample catotelm (anaerobic zone) horizons [71–73], and a Dutch auger was used for underlying mineral soils. Profile descriptions consisted of the horizon depth, Munsell© color, percentage of plant fiber content, rubbed fiber content, humification based on the von Post [74] scale, boundary transitions, and description of identifiable plant fibers.

Percentage of plant fiber content was determined in the field. Plant fibers were defined as pieces of plant tissue showing remnant cellular structures that are less than 2 mm in cross section, but large enough to be retained on a 100-mesh (0.15 mm) sieve [75]. Soil Taxonomy [69] specified that living plant tissue and organic materials greater than 2 mm in cross section were excluded from the fiber content. Rubbed fiber content was determined by rubbing the samples between the thumb and forefinger ten times, rolling the sample into a ball, breaking the ball in half, and making a visual assessment of the percentage of fibers that remain [76]. Percentage of rubbed plant fibers determined the organic soil horizon designations: Oi, Oe, or Oa. Oi denotes organic horizons composed of slightly decomposed fibric material (peat), with more than 40% of fibers being present after rubbing. Sphagnum moss was a strong indicator of fibric material; usually, only the upper 2 to 3 cm of Sphagnum is living tissue and is not considered part of the solum. The dead and decaying Sphagnum, below the upper 2 to 3 cm, is reddish and fibrous in nature. Oe designated organic horizons with intermediate decomposition hemic material (mucky peat), with 17% to 40% of fibers being present after rubbing. Hemic material typically had the look and soft feel of mature compost; it was usually brown in color with easily discernable plant fibers. Oa designated organic horizons that were highly decomposed sapric material (muck), with less than 17% of fibers being present after rubbing. Sapric material was usually black and had a greasy feel; when air-dried it was a lightweight moderately hard mass [77].

Peat humification was estimated visually with freshly extracted peat and gave a reasonably accurate assessment for the field description of peat stratigraphy [41]. Humification, assigned an H value from 1 to 10 on the von Post scale, was gauged in the field by compressing a soil sample in one hand, catching the squeezed material and water/soil solution in the other hand. The color and turbidity of the free water and the distinctness of the visible plant structure was used to assign a von Post H value [78,79]. The von Post humification scale is used extensively outside of the United States because it is "quick and, with practice, is consistent, more precise, and more accurate than sieving methods" [79].

Taking into account vegetation, ecosystem, microtopography, and water depth, a minimum of two individual core locations within each peatland were selected to sample for laboratory analysis. Locations selected for laboratory analysis were cored three separate times within a 30 cm radius of a central point. The first core at a location was used for the soil profile description, a second core for bulk density samples, and a third core for all other laboratory analyses. Bulk density samples were collected to avoid compaction and utilized careful measurements of peat volume [41,71]. Core samples were collected directly from a McCauley peat corer, placed in cut lengths of PVC tubes, wrapped with plastic foil, sealed with tape, and labeled. Due to 20th century surface disturbances, including logging and an off-road motorcycle race, sampling shallow peat cores and sampling the acrotelm were not a focus of this research.

2.2. Laboratory Methods

CVNWR secured funding through U.S. Fish and Wildlife Service, in conjunction with the Radiocarbon Collaborative, sponsored jointly by the USDA Forest Service, University of California Irvine (previous mass spectrometry conducted at Lawrence Livermore National Lab in Livermore, California), and Michigan Technological University, to provide radiocarbon dating of 52 samples from 11 cores. Radiocarbon dating samples were chosen based on core locations within the peatlands and horizon depth within the profile, focusing on basal peat, horizon breaks within the catotelm, and the sedimentary sequence of the deepest cores [34,80,81]. Standard radiocarbon ages were calibrated to dates (cal yr BP) using an OxCal 4.2 and IntCal13 Northern Hemisphere calibration curve [82,83].

Bulk density, organic matter content, fiber content, and pyrophosphate color laboratory analysis on individual horizons in each of the 30 laboratory analysis cores were conducted in the labs of the Division of Plant and Soil Sciences of West Virginia University. Laboratory analysis procedures in the UDSA-NRCS Kellogg Soil Survey Laboratory Methods Manual [84] were followed, with the explicit intention of soil classification according to Soil Taxonomy [69].

Bulk density is an indirect measure of organic soil decomposition [85]. Less decomposed peat tended to be of low bulk density and were likely deposited under wet conditions that promoted rapid accumulation and burial of organic matter [41]. More decomposed, or humified, muck tended to be of higher bulk density and was likely deposited under drier conditions with slow accumulation and burial of organic material. Organic matter bulk density was used as a simple proxy of the varying degree of total peat decomposition and to infer past surface moisture conditions [41,85,86]. Bulk density was measured in the laboratory using oven-dried weight of a known volume of organic soil sample.

Organic matter content is naturally high in peatlands but can vary substantially due to mineral inputs including exogenous waterborne and wind-blown materials [41]. Loss on ignition was utilized to determine mineral and organic matter contents of the soils. Mineral content consists of ash and mineral particles that remain after removal of organic matter. Determination of organic matter by loss on ignition was a taxonomic criterion for organic soil materials [84]. Organic matter content was calculated by taking the dry weight minus weight after ashing overnight at 550 °C, divided by dry weight.

Percentage of plant fibers is used in Soil Taxonomy to determine sapric, hemic, and fibric organic materials for classification [87–89]. Fiber content can be complex and variable, differing between soil horizons, as well as laterally across a peatland [89]. Using known-volume samples and washing through a 100-mesh (0.15 mm) sieve with tap water, the percentage of fibers retained on the sieve was estimated, then rubbed and washed again, to determine rubbed fiber content and thus the decomposition state of soil organic matter and horizon designation [69,89].

Pyrophosphate color was another requirement for determining decomposition class for the taxonomic classification of Histosols [89,90]. The procedures for testing pyrophosphate color entailed adding an aqueous sodium pyrophosphate solution to a pre-measured soil sample. The color value and chroma of the extract were evaluated by moistening a chromatographic strip in the solution and comparing color with the 10YR Munsell© soil color chart [69,79,84].

3. Results

Generally, most soil profiles in CVNWR peatlands had similar horizonation trends. The acrotelm consisted of approximately 20 cm of fibric soil material, typically underlain by less than 10 cm of sapric soil material located at the water table. The catotelm consisted of various thicknesses of a combination of hemic (moderately decomposed) and sapric (highly decomposed) soil materials. Radiocarbon dates and peat accumulation rates are reported in Table 1 [90]. Sequential radiocarbon dates were obtained for seven cores, six of which (cores 1.86, 2.09, 3.13, 4.19, 5.12, and 5.17) had basal peat dates ranging from ~18,600 to ~15,200 cal yr BP, during or immediately after Heinrich Stadial 1, correlating to a hemic soil horizon that also spanned the Greenlandian Age. These cores also all contained a sapric horizon dating to the Northgrippian Age and another hemic horizon dating to the Meghalayan Age. The seventh core (Core 4.02) with sequential radiocarbon dates had a late Northgrippian Age basal peat date of ~4600 cal yr BP. Peat accumulation rates (Table 1) were calculated as the thickness of accumulated peat in mm divided by the corresponding radiocarbon dated interval [91]. Peat accumulation rates varied from a maximum of 1.34 mm/yr to a minimum of 0.02 mm/yr, with a mean of 0.14 mm/yr (calculated as the mean of the overall whole core rates at each core with sequential dates). Peat accumulation rates between ~15,800 and ~12,500 cal yr BP averaged 0.24 mm/yr. The net peat accumulation declined to a mean of 0.11 mm/yr between ~11,700 and ~8600 cal yr BP, generally correlating to the

Greenlandian Age. Few radiocarbon dates were obtained on peat of Northgrippian Age; hence, only two cores include well-constrained mid-Holocene peat accumulation rates. Core 3.13 had a peat accumulation rate of 0.02 mm/yr between ~11,700 and ~5900 cal yr BP, and Core 5.17 had a peat accumulation rate of 0.04 mm/yr between ~10,300 and ~5400 Cal yr BP. These may be the lowest of any time since the onset of peat accumulation, a trend reinforced by the scarcity of peat of this age. Exceptionally high peat accumulation rates between ~4200 and ~2000 cal yr BP averaged 0.50 mm/yr, coeval with the onset of the Meghalayan Age. The last 2000 years of peat development in CVNWR was represented by only three dates, but generally show very low peat accumulations rates averaging 0.08 mm/yr, which may reflect a reduction in peat accumulation, or mixing of surface vegetation into near-surface soil horizons.

Table 1. CVNWR radiocarbon dates and accumulation rates. Dated material consisted entirely of bulk peat samples. Accumulation rates were calculated as the thickness of accumulated peat divided by the corresponding interval between calibrated median radiocarbon ages. Samples 41 and 42 were reanalyzed due to a stratigraphic inversion, likely caused by procedural error. Dates on samples 41* and 42* were in expected stratigraphic order, so these age determinations were used in analysis and interpretation. The $_{+}$ symbol denotes radiocarbon dates with overlapping 95% confidence intervals; mid-points were used to calculate peat accumulation rates which were used for data interpretation.

Laboratory ID	Sample No.	Core No.	Depth (cm)	Standard Radiocarbon Age		intCal13 Calibrated Dates 95% Confidence Interval		Median Cal yr BP	Accumulation Rate mm/yr
				^{14}C Age	±	From	To		
CAMS-171742	25	1.82	128–130	12,810	40	15,449	15,109	15,258	
CAMS-172756	32	1.86	2–4	1225	30	1260	1065	1153	0.05
CAMS-172757	33	1.86	40–42	7880	35	8953	8587	8675	0.08
CAMS-172762	38	1.86	59–61	9600	30	11,128	10,774	10,928	0.18
CAMS-172763	39	1.86	86–88	10,475	35	12,560	12,147	12,451	0.82_{+}
CAMS-172764	40	1.86	100–102	10,635	30	12,690	12,559	12,621	0.08_{+}
CAMS-171738	21	1.86	127–129	13,155	40	1,6002	15,637	15,807	
CAMS-171739	22	2.05	119–121	15,045	40	18,435	18,099	18,284	
CAMS-172760	36	2.09	15–17	3550	35	3960	3720	3844	0.05
CAMS-172761	37	2.09	40–42	8035	35	9021	8775	8909	0.04
CAMS-172758	34	2.09	65–67	12,455	45	14,961	14,251	14,598	0.16
CAMS-172759	35	2.09	80–82	12,985	40	15,732	15,315	15,528	0.33
CAMS-171737	20	2.09	92–94	13,225	40	16,069	15,730	15,896	
CAMS-172750	26	3.13	11–13	1925	30	1947	1817	1873	0.11
CAMS-170482	10	3.13	27–29	3155	30	3450	3269	3382	0.45
CAMS-172751	27	3.13	50–52	3590	30	3977	3833	3894	0.07
CAMS-170483	11	3.13	64–66	5180	30	5991	5905	5936	0.02
CAMS-172752	28	3.13	75–77	10,095	40	11,954	11,404	11,687	0.06
CAMS-172753	29	3.13	83–85	11,085	35	13,063	12,824	12,960	0.20
CAMS-170484	12	3.13	94–96	11,680	30	13,570	13,445	13,510	0.08
CAMS-172754	30	3.13	120–122	13,815	40	16,946	16,488	16,715	0.23
CAMS-170485	13	3.13	165–167	15,375	35	18,759	18,544	18,653	
CAMS-171740	23	3.14	121–123	13,870	40	17,009	16,573	16,802	
CAMS-170478	6	4.02	7–9	420	35	530	326	486	0.06
CAMS-170479	7	4.02	17–20	2130	30	2299	2001	2111	0.44
CAMS-170480	8	4.02	76–79	3240	30	3560	3388	3460	0.35
CAMS-170481	9	4.02	117–120	4095	35	4814	4446	4607	
CAMS-172755	31	4.09	151–152	4380	40	5212	4852	4942	
CAMS-172770	46	4.19	30–32	2490	30	2730	2460	2584	0.61
CAMS-172771	47	4.19	60–62	2925	30	3164	2971	3072	0.52
CAMS-172772	48	4.19	80–82	3235	30	3558	3385	3453	0.58
CAMS-172773	49	4.19	120–122	3775	35	4281	3992	4146	0.05
CAMS-172774	50	4.19	165–167	11,235	35	13,164	13,041	13,097	0.21
CAMS-171741	24	4.19	211–213	12,850	40	15,545	15,160	15,315	

Table 1. *Cont.*

Laboratory ID	Sample No.	Core No.	Depth (cm)	Standard Radiocarbon Age		intCal13 Calibrated Dates 95% Confidence Interval		Median Cal yr BP	Accumulation Rate mm/yr
				^{14}C Age	±	From	To		
CAMS-170473	1	5.12	16–20	2080	30	2140	1952	2050	0.64
CAMS-170474	2	5.12	51–53	2495	30	2732	2466	2585	1.34
CAMS-170475	3	5.12	82–85	2725	30	2873	2761	2817	0.04
CAMS-170476	4	5.12	114–116	9010	30	10,235	10,170	10,204	0.15
CAMS-170477	5	5.12	197–199	13,105	35	15,940	15,540	15,733	
CAMS-171732	15	5.17	18–20	2070	30	2123	1950	2039	0.68
CAMS-171733	16	5.17	70–72	2705	30	2857	2756	2804	0.39
CAMS-172765	41	5.17	85–87	3800	30	4288	4088	4187	
CAMS-174232	41*	5.17	82–84	2970	30	3230	3007	3135	0.37
CAMS-172766	42	5.17	120–122	2930	30	3169	2974	3080	
CAMS-174233	42*	5.17	122–124	3820	40	4406	4091	4217	0.07
CAMS-172767	43	5.17	130–132	4580	30	5447	5066	5302	0.63_{+}
CAMS-172768	44	5.17	140–142	4720	45	5584	5322	5460	0.04_{+}
CAMS-171736	19	5.17	161–163	9160	45	10,483	10,231	10,323	0.12
CAMS-172769	45	5.17	173–175	9930	30	11,590	11,241	11,312	0.12
CAMS-171735	18	5.17	196–198	11,360	35	13,290	13,115	13,203	0.28
CAMS-171734	17	5.17	225–227	12,310	35	14,531	14,075	14,237	0.55
CAMS-171731	14	5.17	288–290	12,890	40	15,598	15,210	15,382	

The field investigation resulted in re-mapping the five pre-existing NRCS soil polygons, originally totaling 187 hectares, now totaling 246 hectares (Figure 1). Out of the 100 soil profiles examined for this study, 12 were determined to be Entisols and will not be discussed further. The 88 remaining Histosol profiles were separated into five types (A–E) based upon the sequence of horizons in the catotelm (Table 2 and Figure 2). The soil profiles investigated in CVNWR peatlands were very similar in terms of acrotelm horizonation. The acrotelm usually consists of ~20 cm of fibric soil material, underlain by ~10 cm of sapric soil material located near the water table. This sapric horizon at the water table has the greatest humification [36] throughout the project area. Due to the legacy of surface disturbance possible with the CVNWR peatlands, it was determined by the authors that pedomemory within the peat stratigraphy was best retained within the catotelm, which has a slow decomposition rate [37] and no apparent history of disturbance. CVNWR soil profile catotelms consisted of varying thicknesses of a combination of hemic and sapric soil materials (Figure 3). Figure 3 shows the generalized pedogenic development of the five types (A–E) of catotelm horizon sequences represented in the 88 Histosol profiles at CVNWR; each is discussed below.

Type A soil profiles (Figure 4) had a catotelm comprised entirely of hemic soil horizons (H). This horizonation occurred in four of the five peatlands (Table 2 and Figure 2). Of these 10 soil profiles, two had radiocarbon dates and none had laboratory data. Sequential radiocarbon dates in Core 4.02 (Figure 4) and a basal peat date in Core 4.09, show that these Type A (H) profiles had basal peat dates of 4600 cal yr BP and 4900 cal yr BP, respectively. The late Northgrippian peat initiation in these two Type A (H) soil profiles was ~10,000 years younger than the onset of peat accumulation in other dated CVNWR cores.

Table 2. Categorized catotelm profile type distribution amongst the five peatlands. S and H represent Sapric (highly decomposed) and Hemic (moderately decomposed). Type A has only Hemic horizons, Type B has Sapric over Hemic horizons, Type C has Hemic over Sapric over Hemic horizons, Type D has only Sapric horizons, and Type E has Hemic over Sapric horizons.

Soil Profile Type in the Catotelm		**Peatland 1**		**Peatland 2**		**Peatland 3**		**Peatland 4**		**Peatland 5**		**Type Totals**
		Cores	**Data**	**Cores**	**Data**	**Cores**	**Data**	**Cores**	**Data**	**Cores**	**Data**	
Type A (H)		2		0		4		3		1		10
	with lab data and C14 dates		0		0		0		0		0	
	with C14 dates		0		0		0		2		0	
	with lab data		0		0		0		0		0	
	only field descriptions		2		0		4		1		1	
Type B (SH)		17		4		2		0		1		24
	with lab data and C14 dates		2		2		0		0		0	
	with C14 dates		0		1		1		0		0	
	with lab data		2		1		0		0		0	
	only field descriptions		13		1		1		0		1	
Type C (HSH)		0		2		6		6		13		27
	with lab data and C14 dates		0		0		1		1		1	
	with C14 dates		0		0		0		0		1	
	with lab data		0		2		0		0		4	
	only field descriptions		0		0		5		5		7	
Type D (S)		3		3		3		2		0		11
	with lab data and C14 dates		0		0		0		0		0	
	with C14 dates		0		0		0		0		0	
	with lab data		0		0		0		0		0	
	only field descriptions		3		3		3		2		0	
Type E (HS)		3		0		4		8		1		16
	with lab data and C14 dates		0		0		0		0		0	
	with C14 dates		0		0		0		0		0	
	with lab data		0		0		3		3		1	
	only field descriptions		3		0		1		5		0	
Totals for each peatland		25		9		19		19		16		88

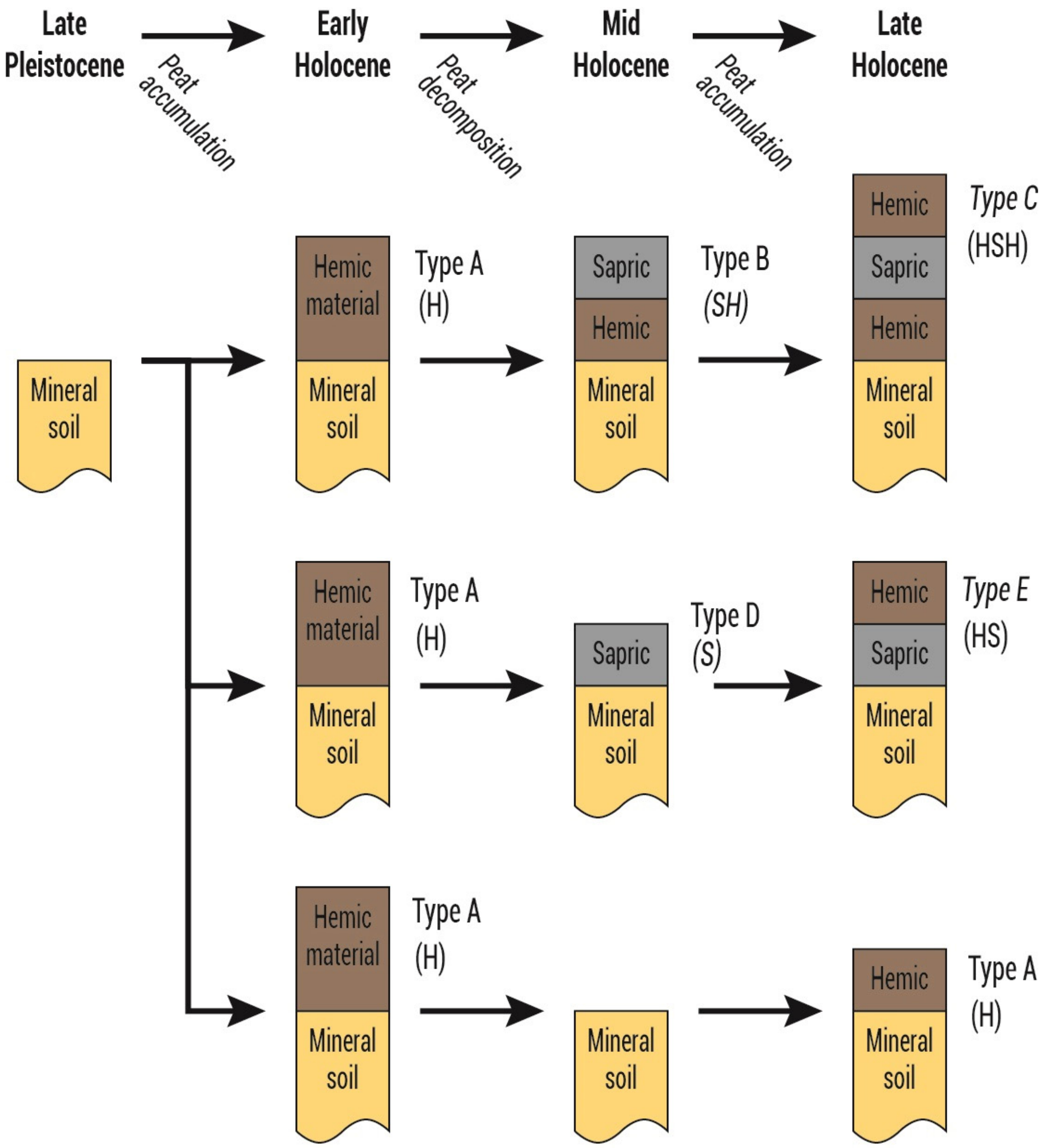

Figure 3. Possible development pathways for the five profiles types amongst CVNWR organic soil cores.

Type B soil profiles (Figure 5) had a catotelm sequence of a sapric horizon underlain by a hemic horizon (SH). This horizonation occurred in four of the five peatlands (Table 2 and Figure 2). This profile type was more numerous in the shallow peatlands. Type B (SH) profiles comprised almost all of Peatland 1, surrounded the cluster of Type C (HSH) profiles in Peatland 2, were nestled next to an upland bedrock area in Peatland 3, were not represented in Peatland 4, and were insignificant in Peatland 5. Of these 24 soil profiles, three had laboratory data and radiocarbon dates, two had only radiocarbon dates, and three had only laboratory dates. Two cores (1.86 and 2.09) with sequential radiocarbon dates had Type B (SH) soil profiles, with a catotelm sapric horizon spanning the Northgrippian Age (Figure 5).

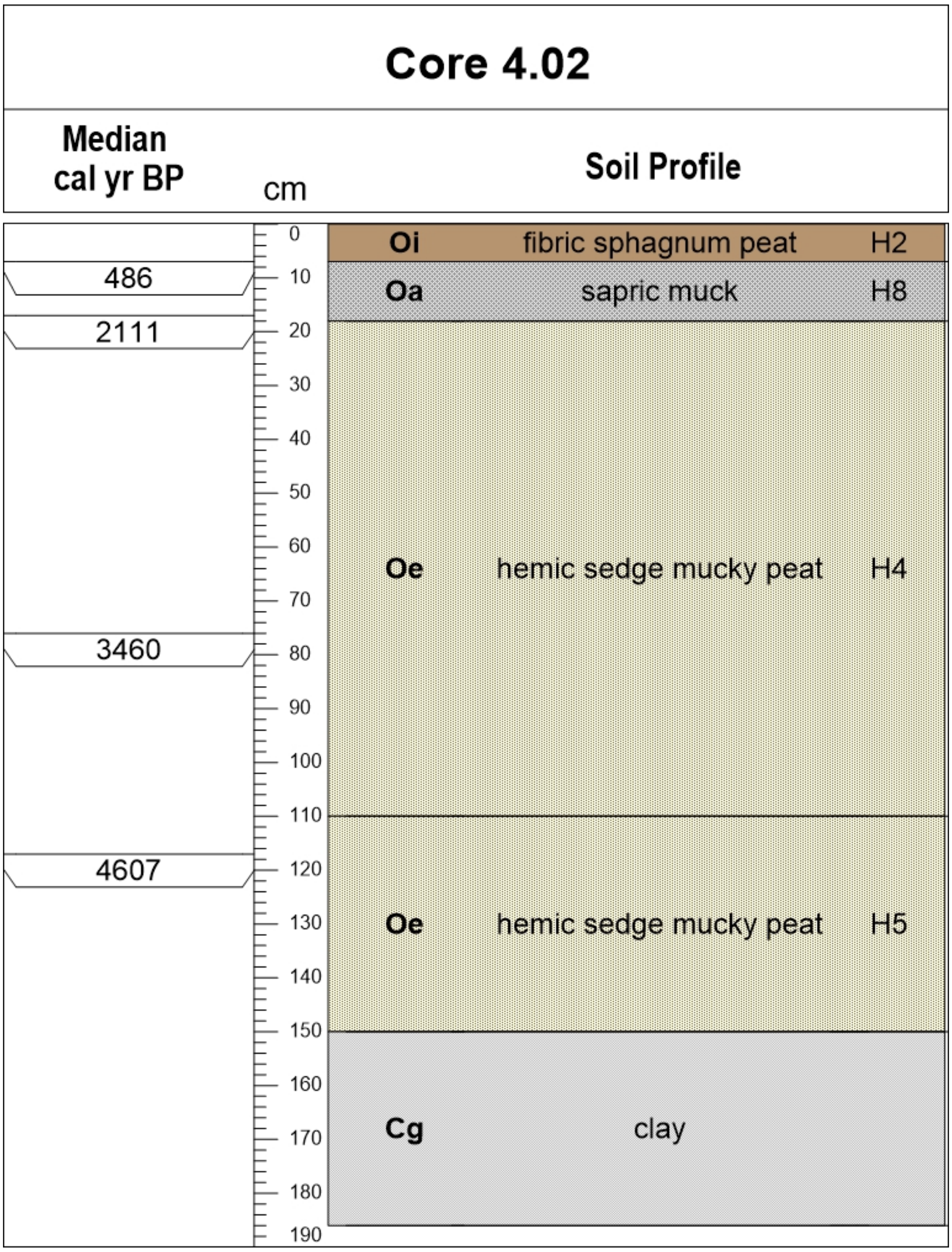

Figure 4. Soil profile of Core 4.02, representing Type A (H) profiles.

Type C soil profiles had a distinct horizonation (Figures 3 and 6) with a catotelm layered as a hemic soil horizon, underlain by a sapric horizon, underlain by another hemic horizon (HSH). This distinct Type C (HSH) horizonation was the most numerous of the 88 profiles examined and occurred in four of the five peatlands (Table 2 and Figure 2). This profile type was more numerous in larger and deeper peatlands. Type C (HSH) soil profiles occurred clustered in the center of Peatlands 2, 3, and 4, and comprised almost all of Peatland 5. Of the 27 Type C soil profiles, three had laboratory data and radiocarbon dates, one had only radiocarbon dates, and five had only laboratory data. Four cores (3.13, 4.19, 5.12, and 5.17) with sequential radiocarbon dates had Type C (HSH) soil profiles, with a catotelm sapric horizon dating to the Northgrippian Age (Figure 6).

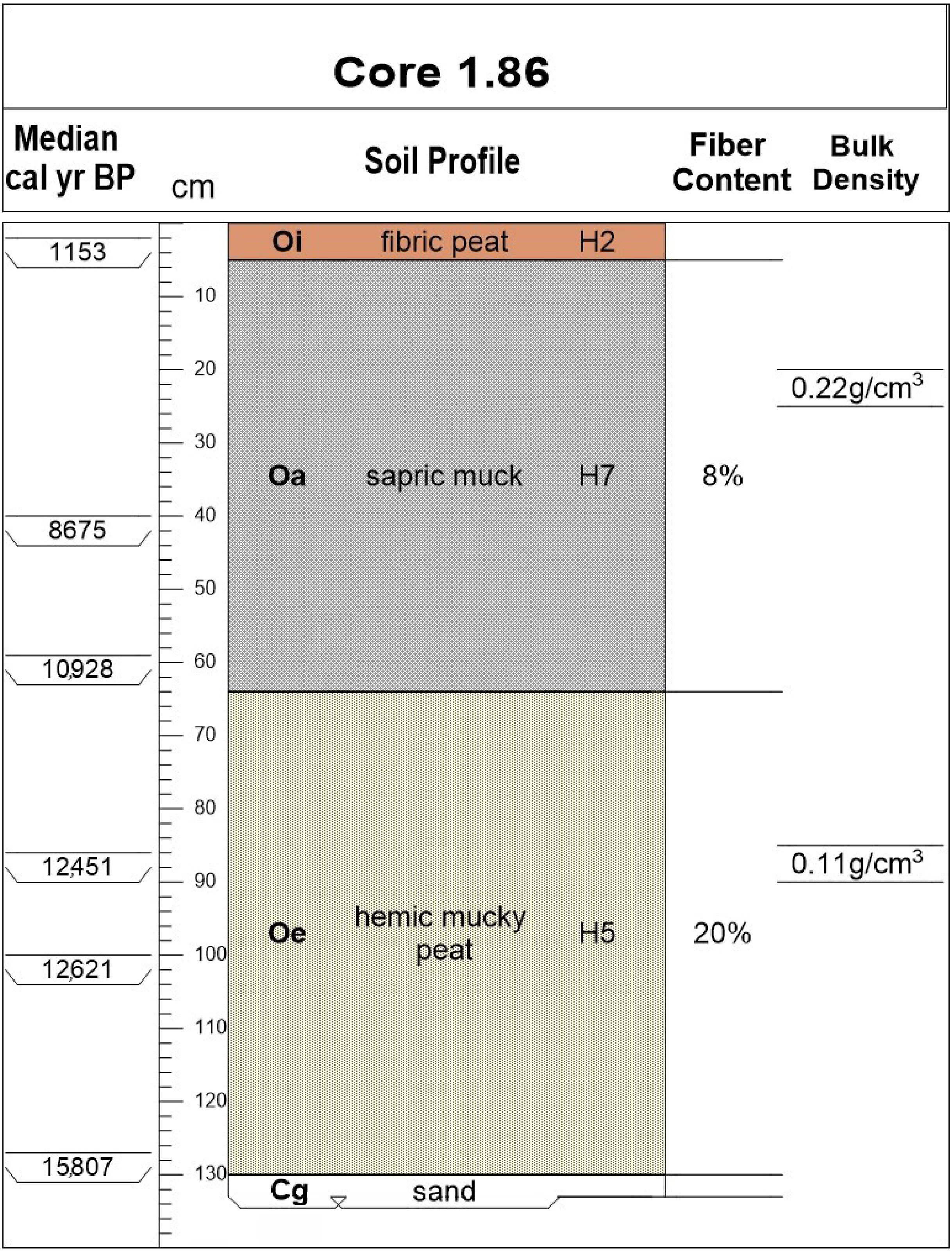

Figure 5. Soil profile of Core 1.86, representing Type B (SH) profiles.

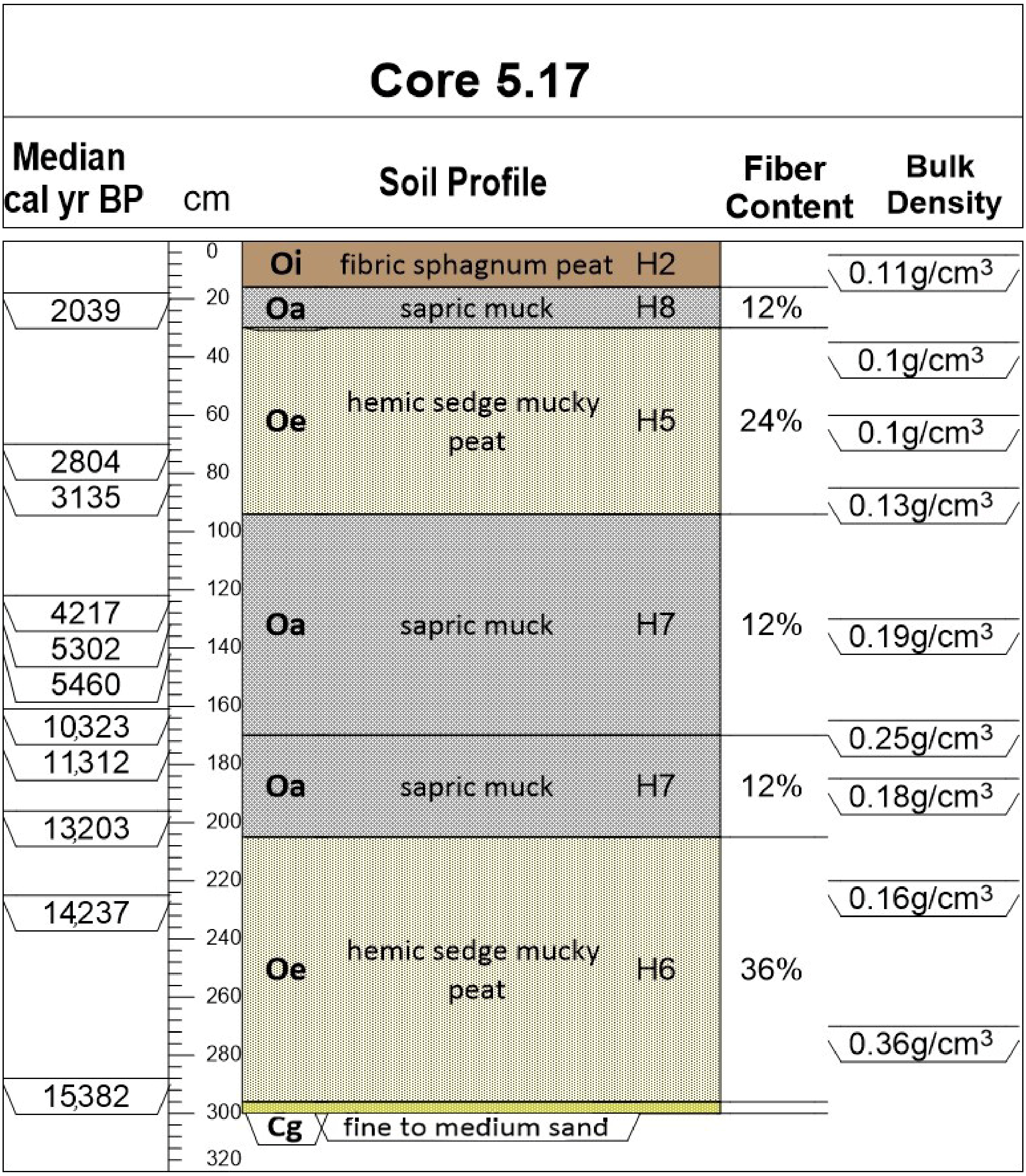

Figure 6. Soil profile of Core 5.17, representing Type C (HSH) profiles.

Type D soil profiles (Figure 7) had a catotelm comprised entirely of sapric soil horizons (S). This horizonation occurred in four of the five peatlands (Table 2 and Figure 2). Most Type D (S) soil profiles occurred along the periphery of the shallow peatlands. None of these 11 soil profiles had laboratory data or radiocarbon dates.

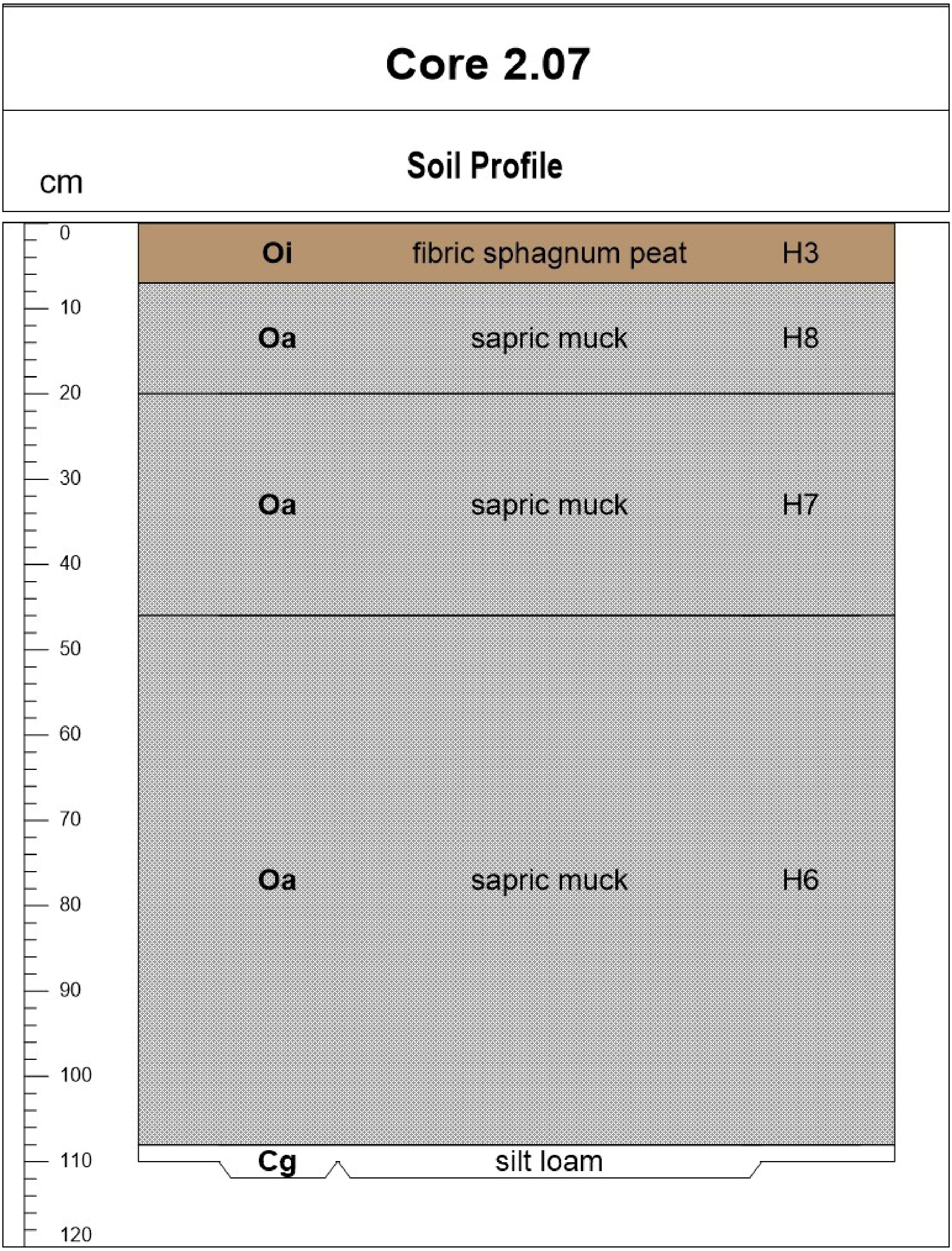

Figure 7. Soil profile of Core 2.07, representing Type D (S) profiles.

Type E soil profiles had a catotelm sequence of a hemic horizon underlain by a sapric horizon (HS) (Figure 8). This horizonation occurred in four of the five peatlands (Table 2 and Figure 2). Type E (HS) soil profiles typically occurred surrounding clusters of Type C (HSH) soil profiles. Type E (HS) profiles were generally shallower than Type C (HSH) profiles. Of 16 soil Type E profiles, seven had laboratory data but none had radiocarbon dates.

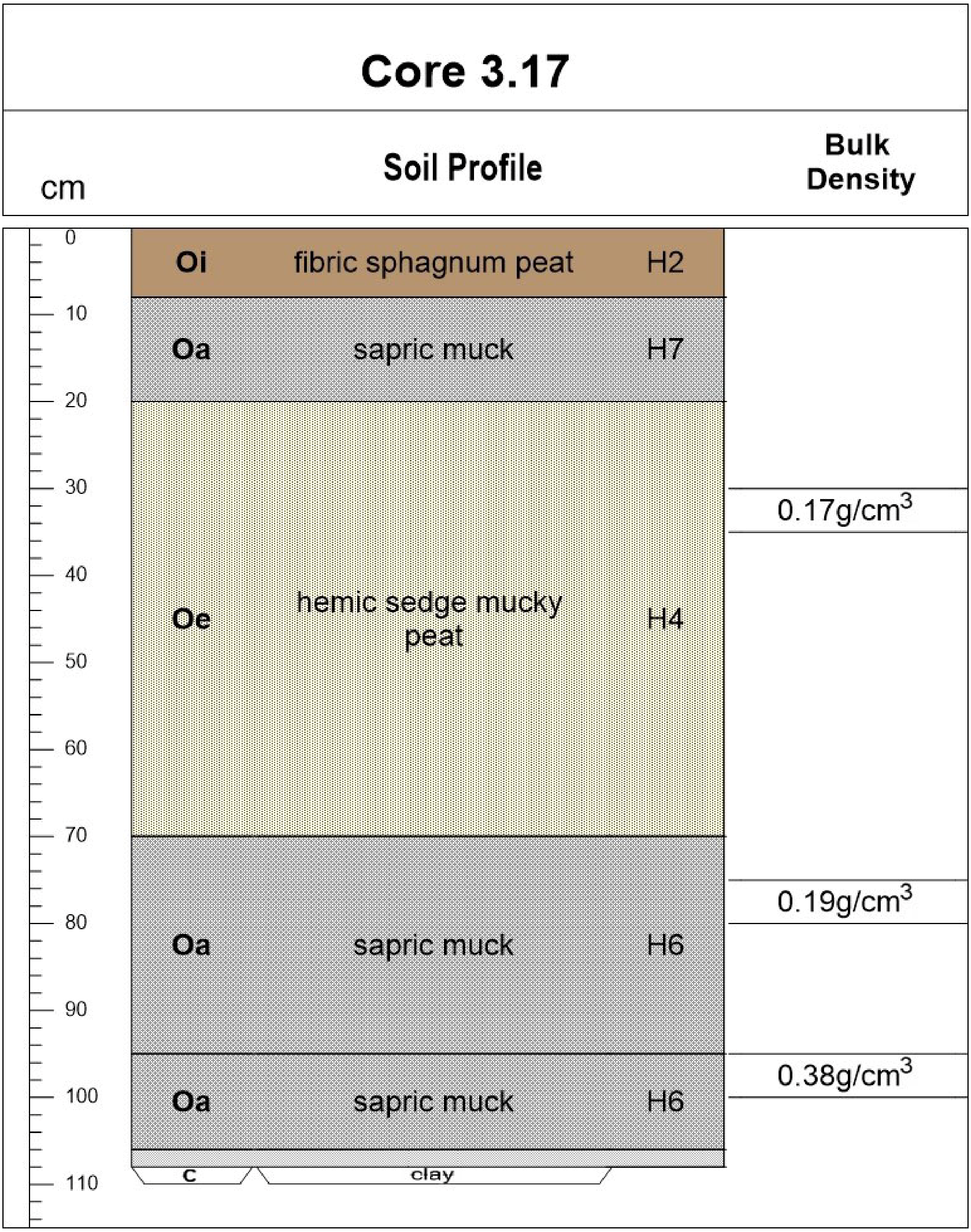

Figure 8. Soil profile of Core 3.17, representing Type E (HS) profiles.

Figure 2 summarizes the geographical distribution of soil profile types. Peatland 1 had the most cores and was dominated by Type B (SH) profiles. Peatland 1 was the easiest to access for field visits, and had the most soil profiles, biasing statistics on Type B (SH) profiles. Peatland 2 had the fewest cores, and a pattern of Type C (HSH) profile in the center surrounded by Type B (SH) profiles, and Type D (S) profiles in shallow areas peats along the periphery. Peatland 3 had clusters of all five profile types. Peatland 4 had Type C (HSH) profiles clustered on the thickest peat, surrounded by Type E (HS) profiles, and a patch of Type A (H) profiles. Peatland 5 was the largest peatland and was dominated by Type C (HSH) profiles.

4. Discussion

Peatlands formed after the LGM hold a pedomemory of the latest Pleistocene and Holocene climatic fluctuations [92,93]. This study begins the reconstruction of the Central Appalachian paleoclimate through peat stratigraphy which is the characterization of the peat horizonation of Histosols that reveal the peatland surface wetness dynamics within CVNWR. A key observation for this reconstruction is the fact that sapric horizons are considered indicative of drier warmer conditions, whereas hemic horizons are associated with wetter, cooler conditions [40,45]. When drained, fibric and hemic materials decompose to form sapric materials [69]. Warmer temperatures generally increase the rates of plant matter decomposition. Humification data indicate changes in the time span from the time of the plant death to the deceased plant matter being incorporated into the anaerobic catotelm [45]. Plant matter decomposition rates sharply decrease in the catotelm, and become independent of all but the most extreme climatic fluctuations [37,86]. A lowered water table would expose previously buried peat to aerobic conditions, adjusting the acrotelm–catotelm boundary, exposing hemic material formerly in the catotelm to aerobic conditions and secondary decomposition [94,95]. The climate influences the water table depth, which determines whether organic soil material will accumulate rapidly, accumulate slowly, not accumulate, or decompose. A lowered water table could result from a warmer, drier climate, and therefore increase the decomposition of peat formerly preserved within the catotelm. Thus, Histosol horizons represent a proxy for water table position at the time of deposition and thereafter [45]. While peat humification is aided by other paleoclimate proxies to reconstruct past climates [44], the abundance of observations within this investigation adds breadth to existing regional and local peat paleoclimate reconstructions and provides new data that are useful to assess the synchronization of observed paleoclimate data within the region [90].

The mid-Holocene Northgrippian Age, defined as 8236 to 4250 cal yr BP [14–16], was characterized in North America by a rapid rise in temperature. The mid-Holocene Climatic Optimum Maximum was the period of maximum warmth during the Northgrippian Age. The onset and conclusion of this Climatic Optimum varied from region to region within North America [20–22]. The Climatic Optimum saw climactic conditions considerably warmer than today [96–101]; however, evidence from eastern North America suggests the significant regional variability of moisture associated with that warmth [22,102–104]. The isotopic analysis of soil organic matter from eastern Pennsylvania, North Carolina, and Tennessee and microscopic charcoal from lake sediments in Tennessee suggest warm, dry conditions during the mid-Holocene Climatic Optimum [19,105–107].

The warm and dry signature of the Climatic Optimum has been identified in the central Appalachian region. Watts [108] found that the paleo-vegetation of central Appalachia indicated mid-Holocene water tables that are lower or less stable than today. Springer et al. [100] found evidence of a mid-Holocene warm climate in southeastern West Virginia in stable isotopes of stalagmites and clastic cave sediments. Driese et al. [97] found that mid-Holocene warm and dry climatic conditions accelerated the weathering of previously deposited fluvial gravel deposits in southeastern West Virginia. The mid-Holocene Northgrippian Age ended with a pronounced climatic event at 4200 cal yr BP that manifested in the mid-continent of North America as a widespread and severe drought [14,16,21,23,24,109].

The microtopography and hydrology of peatland surfaces and edaphic hydrology are irregular and dynamic [37,110,111] and are presumably the reason for the initiation of peat accumulation in the late Northgrippian Age, as displayed in the Type A (H) soil profiles. Decomposition during the mid-Holocene Climatic Optimum in these specific locations may have been so great, resulting from a drastically lowered water table, that the earlier deposited peat may have decomposed completely, not leaving behind a remnant sapric horizon as in the Type E (HS) soil profile scenario (Figure 3). The observations of Peatland 4 during this field investigation did include both small ponds and localized depressional areas with no surface vegetation and an absent acrotelm. As in Type C and E profiles, Type A (H) soil profiles exhibit the rapid peat accumulation in the middle Meghalayan Age, represented by a hemic horizon within the catotelm.

Type B (SH) soil profiles, as represented by Core 1.86 (Figure 5), show rapid peat accumulation in the late Pleistocene, corresponding to the catotelm hemic soil materials in these soil profiles (Figure 3). As the local climate of the early Holocene Greenlandian Age continued to warm, peat continued to slowly accumulate, followed by an even slower peat accumulation during the mid-Holocene Northgrippian Age, represented as a sapric horizon spanning the Greenlandian Age to the middle Meghalayan Age. This is consistent with a drier mid-Holocene Climatic Optimum resulting in a lowered water table. However, Type B (SH) soil profiles do not show the late Meghalayan Age hemic horizon of rapid peat accumulation found in Type C (HSH) and E (HS) soil profiles. It is possible that the hydrology of Peatland 1, where most Type B (SH) soil profiles are located, changed during the Northgrippian Age, possibly due to local channel incision or differential level development affecting peatland surface wetness. Without a return of the wetter, high-groundwater conditions, these locations did not develop a hemic horizon at the soil surface.

Type C (HSH) soil profiles within CVNWR contain a pedomemory of a wet–dry–wet sequence for the local post LGM climate (Figure 3), which is supported by the radiocarbon dates taken from these cores and concurs with other central Appalachian paleoclimate records. Type C (HSH) soil profiles, as represented by Core 5.17 (Figure 6), record late Pleistocene peat deposition in the catotelm as a hemic horizon. Peat accumulated at a slower rate during the early Holocene Greenlandian Age. However, during the Northgrippian Age, peat accumulation slowed drastically, likely in response to a lowered water table under a relatively dry climate. The sapric horizon in the Type C (HSH) soil profiles spans the Greenlandian, Northgrippian, and early Meghalayan ages. The hemic horizon deposited above this sapric material in Type C (HSH) soil profiles is associated with renewed peat accumulation in the middle and late Meghalayan Age, indicating a wetter local climate with a raised water table following the mid-Holocene Climatic Optimum.

Type D (S) soil profiles are shallow and primarily located along the edges of the peatlands where water table depths fluctuate the greatest, exposing the catotelm frequently to aerobic conditions and promoting decomposition. Due to their drier setting and lack of radiocarbon dates, these Histosols cannot be used to infer climate.

Although no Type E (HS) soil profiles have radiocarbon dates, the pattern is consistent with the low peat accumulation of the Northgrippian Age, where peatland surface wetness was reduced so greatly in these generally shallow areas that secondary decomposition altered most of the previously deposited hemic material and is now represented as a sapric material (Figure 3). More hemic material was deposited into the catotelm late in peat development, possibly because climatic moisture increased in the Meghalayan Age, resulting in a raised water table.

5. Conclusions

Using peat stratigraphy and well-dated soil profiles, we have found proxy evidence of a drier local climate during the mid-Holocene Climatic Optimum in the central Appalachian Mountains. Correlating the calibrated radiocarbon dates with the soil profile descriptions and laboratory data revealed that the catotelm in the Histosols of CVNWR contains the pedomemory of paleoclimatic fluctuations represented as an upper hemic horizon, underlain by a sapric horizon, underlain by another hemic horizon. Sapric horizons are indicative of drier warmer conditions, whereas hemic horizons are associated with wetter cooler conditions. The sandwiched sapric horizon dates to the mid-Holocene Climatic Optimum. The extremely low peat accumulation rate during this time most likely results from an increase in the decomposition rate of the material at the top of the catotelm [112] due to a lowered water table associated with a climatic change from cool and wet in the Greenlandian Age to warm and dry during the Northgrippian Age (Figure 3). The pedomemory revealed in the CVNWR soil profiles concurs with other central Appalachian paleoclimate records and also confirms and compliments the existing published literature on the regional paleoclimate for the eastern United States. Peat humification and peat stratigraphy are useful proxy paleoclimate records; understanding how these ecosystems have responded to past climatic changes will help land use managers interpret how these ecosystems might respond to the projected future climate change.

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