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Radiocarbon dating peatland development: Key steps in reconstructing past climate in the central Appalachian Mountains

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A R T I C L E I N F O

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A B S T R A C T

Canaan Valley in West Virginia contains a greater area of peatlands than any other locality in the mid-Atlantic Highlands. Extensive fieldwork focused on peat stratigraphy, combined with high-resolution radiocarbon dating, was used to evaluate five peatlands within Canaan Valley National Wildlife Refuge (CVNWR). One hundred soil cores were profiled and described, 30 with laboratory analysis, including 52 radiocarbon dates. Calibrated basal peat dates from the five peatlands indicate the onset of peat genesis ranged from ~18,600 to ~15,200 cal yr BP. Basal peat dates on the two oldest cores are 1800 to 2200 years older than published dates on peat initiation in any other Appalachian Mountain peatlands. Peat accumulation rates varied from 0.02 mm/yr to 1.34 mm/yr, with a mean of 0.14 mm/yr. Results of age-depth profiles for six well-dated cores consistently exhibit: rapid accumulation during the late Pleistocene (Heinrich Stadial 1, Bølling-Allerød interstadial, and Younger Dryas cold stadial), lower accumulation rates in the early Holocene (Greenlandian Age), even lower accumulation rates during the mid-Holocene (Northgrippian Age), and the most rapid peat accumulation at the onset of the late Holocene (early Meghalayan Age). A paucity of shallow peat dating younger than 2000 BP may reflect a reduction in peat accumulation, or mixing of surface vegetation into near-surface soil horizons. Soil cores from CVNWR suggest a somewhat different peat development history than the process of terrestrialization previously proposed for other peatland ecosystems in the region.

1. Introduction

Central Appalachian peatlands are a southern extension of contemporary boreal ecosystems commonly associated with bogs and fens (Ingham, 1996; Stine et al., 2011; Whitehead, 1965). Allegheny Mountain peatlands range in size from a few hectares to a few hundred hectares (Ingham, 1996). Byers et al. (2007) placed these peatlands within the High Allegheny Wetland Ecological System. This ecological system occurs in a southwest-northeast trending band about 40 km wide and 200 km long along the Allegheny Mountain section of the Appalachian Plateau physiographic province in unglaciated Pennsylvania, Maryland, and West Virginia (Cameron, 1970).

Before the logging era of the 1880s to 1920s, most vegetation in Allegheny Mountain peatlands consisted of hemlock (*Tsuga canadensis*), red spruce (*Picea rubens* Sarg.), and balsam fir (*Abies balsamea* (L.) Mill.) along the wetland edges with *Rhododendron* thickets in the understory, and *Sphagnum* and other mosses blanketing the forest and wetland floor (Francl et al., 2004). Allegheny Mountain peatlands have a rich biodiversity comprised partially of relict populations of once widespread boreal flora (Russell et al., 2009; Wieder et al., 1981). Biodiversity, prior to logging, resulted from dynamically changing landscapes and vegetation during the latest Pleistocene and Holocene climatic fluctuations (Barrington and Paris, 2007; Delcourt and Delcourt, 1986; Martin and Germain, 2016; Russell et al., 2009; Stine et al., 2011).

Paleoecology and development history have been published previously for eight Allegheny Mountain peatlands (Fig. 1): Big Run

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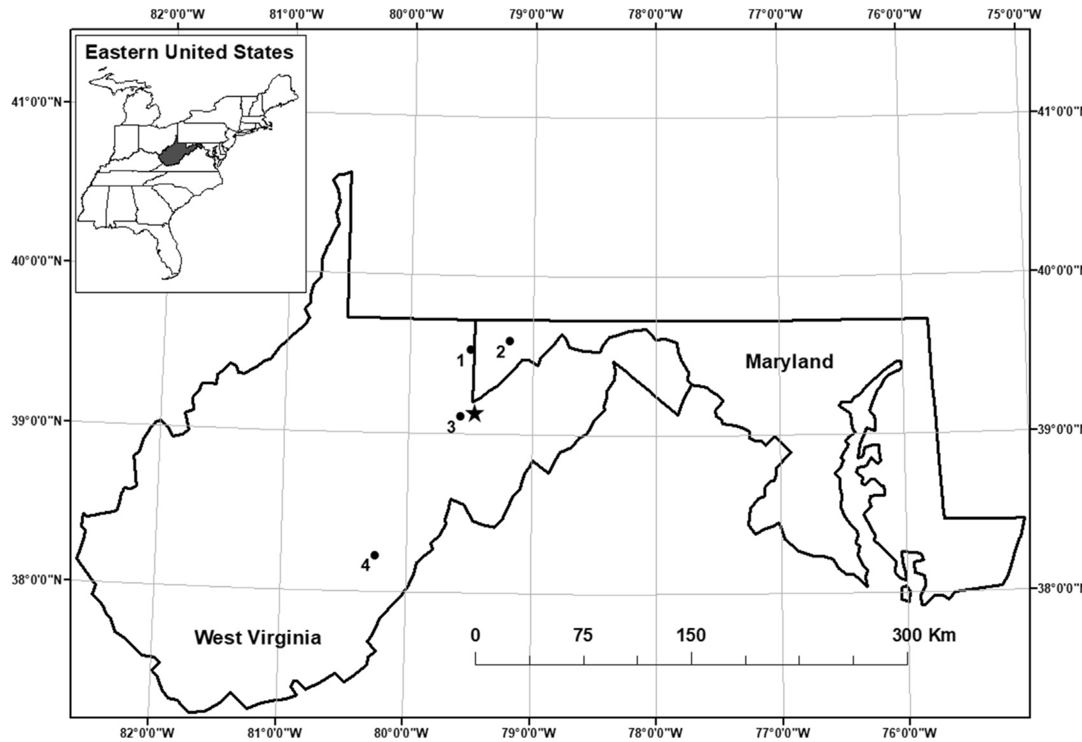

Fig. 1. Within the eastern United States, the location of Canaan Valley is represented as the star, 1 denotes Big Run Bog (Cramer Bog), 2 denotes Buckles Bog (The Glades), 3 denotes Cranesville Swamp, and 4 denotes Cranberry Glades.

Bog (Larabee, 1986), Buckles Bog (Maxwell and Davis, 1972), Cranesville Swamp (Booth et al., 2016; Cox, 1968), four peatlands within Cranberry Glades (Bender et al., 1977, 1979; Darlington, 1943; Edens, 1973; Watts, 1979), and one peatland within Canaan Valley (Cameron, 1970), which was reexamined for this study. Depositional environments are difficult to interpret and compare from previous studies of other peatlands in the region due to inconsistency in sediment profile descriptions and widely varying radiocarbon sample density; however, some generalizations are revealed. Published dates for the eight previously studied Allegheny Mountain peatlands (Fig. 1) outside Canaan Valley were calibrated for this publication using OxCal 4.2 and IntCal13 Northern Hemisphere calibration curve (Bronk Ramsey, 2009; Reimer et al., 2013) for ease of comparison (Table 1). Most published Allegheny Mountain peatland chronologies share a proposed developmental history beginning in the late Pleistocene or Holocene as an open body of water accumulating limnic sediments that evolves through a transitional process of terrestrialization, first into an emergent marsh accumulating organic-rich clays, and the marsh gradually became overgrown with mire plants developing into a peatland accumulating organic soils. The overall paleoecolgical record illustrates a general sequence of the vegetation changing from alpine tundra to open boreal forest, to closed boreal forest, and then finally transitioning into a mixed coniferous-deciduous forest that retained many boreal species.

The primary goal of this research was to establish whether CVNWR, which contains the largest area of peatlands in the Allegheny Mountain physiographic region, has a similar developmental history as the previously studied peatlands in the region. Extensive fieldwork and high-resolution radiocarbon dating were used in evaluation of the climatic and ecosystem developmental history of five peatlands within CVNWR. Climate-ecosystem dynamics are an ever-increasing concern in the face of current and forecasted regional climate change. Preservation of unique ecosystems in the face of anthropogenic use and climate changes is also a concern for the Allegheny Mountain peatlands. Understanding past climate-ecosystem dynamics can be especially useful not only for land-use management decisions but also for understanding future climate-ecosystem dynamics.

1.1. Study area description

Canaan Valley, in Tucker County, West Virginia (Fig. 1), is a high-elevation (980 m), breached anticlinal valley, associated with the Blackwater anticline. Headwaters of Blackwater River, within Cheat River watershed, drain most of the valley, including all study sites. Resistant Pottsville Sandstone caps surrounding mountain ridges with elevations of 1100 to 1300 m, Mauch Chunk siltstones, shales, and immature sandstones form the more easily erodible valley slopes, and Greenbrier Limestone and lower Mauch Chunk siltstones and shales underlie most of the valley floor (Fortney and Rentch, 2003; Matchen, 2015; Matchen et al., 1999). Projecting through limestone bottomlands in the valley center, a low, elongated ridge corresponds to the axis of the anticline; it is comprised of coarse-grained sandstone of the Price Formation (Matchen, 2015).

Canaan Valley lies within the Allegheny Mountain section of the Appalachian Plateaus physiographic province of unglaciated Pennsylvania, Maryland, and West Virginia (Cameron, 1970; Fenneman and Johnson, 1946; Reger and Cleaves, 2008; Sevon, 2018; West Virginia Geologic and Economic Survey, 2017). In general, the Allegheny Mountain section is higher in elevation than adjacent physiography and characterized by broad, open structural bedrock folds. Valley floors, and terraces and interfluves within broad valleys at high elevations (>730 m) of the plateau are typical locations for Allegheny Mountain peatlands (Cameron, 1970; Diehl and Behling, 1982). Some geographic niches in the Allegheny Mountain section are similar climatically to typical higher latitude

Table 1
Calibrated radiocarbon dates compiled from previously published research on other peatlands in the Allegheny Mountains.

Laboratory ID	Location	Publication	Material dated	Depth (cm)	^{14}C age	±	intCal13 Calibrated Dates 95% confidence interval		median cal yr BP
							From	To	
USGS-W2255	Canaan Valley	Cameron (1970)	reed-sedge peat	132	5250	250	6627	5477	6029
A-4261	Big Run Bog	Larabee (1986)	fibrous organic clay	38	210	200	538	20	259
A-4260	Big Run Bog	Larabee (1986)	clayey peat	69	4680	110	5640	5046	5403
A-4264	Big Run Bog	Larabee (1986)	slightly silty organic clay to fibrous organic clay	112	10760	160	13057	12190	12674
A-4263	Big Run Bog	Larabee (1986)	fibrous organic clay	154	12600	170	15436	14153	14858
A-4259	Big Run Bog	Larabee (1986)	fibrous organic clay to slightly silty organic clay	197	13990	220	17584	16322	16975
A-4262	Big Run Bog	Larabee (1986)	slightly silty clay	212	16380	290	20487	19057	19776
A-4258	Big Run Bog	Larabee (1986)	clayey silt	226	16910	340	21331	19591	20424
UGAMS 9988	Cranesville Swamp (1)	Booth et al. (2016)	*Sphagnum*	36	60	25	256	31	71
UGAMS 9987	Cranesville Swamp (1)	Booth et al. (2016)	Charred *Picea* needles & charcoal fragments	41	190	25	296	−4	178
UGAMS 10676	Cranesville Swamp (1)	Booth et al. (2016)	*Sphagnum* and *Picea needles*	57	230	20	307	−3	284
UCIAMS 105039	Cranesville Swamp (1)	Booth et al. (2016)	*Picea* needles	71	950	20	926	796	851
UCIAMS 105038	Cranesville Swamp (1)	Booth et al. (2016)	*Picea* needles	76	1260	20	1274	1176	1223
UGAMS 12021	Cranesville Swamp (1)	Booth et al. (2016)	wood fragment	100	8610	25	9622	9528	9548
UCIAMS 105041	Cranesville Swamp (2)	Booth et al. (2016)	*Picea* needles	72	1255	20	1275	1097	1221
Y-2436	Buckles Bog	Maxwell and Davis (1972)	fibrous peat	74	10530	160	12734	11848	12414
Y-2612	Buckles Bog	Maxwell and Davis (1972)	fibrous peat	161	12320	200	15110	13781	14423
Y-2437	Buckles Bog	Maxwell and Davis (1972)	fibrous peat	191	12640	200	15618	14157	14925
Y-2613	Buckles Bog	Maxwell and Davis (1972)	clayey gyttja	242	15900	240	19805	18703	19210
Y-2619	Buckles Bog	Maxwell and Davis (1972)	clay	249	17400	240	21719	20438	21031
Y-2438	Buckles Bog	Maxwell and Davis (1972)	clay	255	18550	250	22996	21847	22418
USGS-W2253	Buckles Bog	Cameron (1970)	peat	234	13620	600	18196	14691	16465
C-336	Cranberry Glades	Arnold and Libby (1951)	peat	280	9423	840	13082	8775	10890
WIS-794	Cranberry Glades	Watts (1979)	peat	254	4900	65	5879	5476	5641
WIS-933	Cranberry Glades	Watts (1979)	N/A	327	7325	80	8329	7983	8135
WIS-785	Cranberry Glades	Watts (1979)	organic clay	363	12185	140	14759	13737	14112

boreal peatlands (Cameron, 1970) with high average annual precipitation and relatively low average annual temperature (Sencindiver et al., 2015; Walbridge, 1994; Western Regional Climate Center, 2016). Local topography, orographic precipitation, and the frost pocket effect where cold, nocturnal air drains downslope, decreasing temperatures on the valley floor, all accentuate the regional climatic conditions (Walbridge, 1994).

Structurally controlled bedrock valleys and concave bottomlands of the Allegheny Mountains exhibit impeded drainage which developed before the Holocene (Cameron, 1970; Larabee, 1986). Allegheny Mountain peatlands occur in or near the headwaters of first- or second-order streams or occur in specific geologic niches (Ingham, 1996). Canaan Valley is a high elevation (965-1000 m) valley located on the breached Blackwater anticline. Surrounding mountain ridges, with elevations of 1100 to 1300 m, are capped by resistant Pottsville Sandstone; the more easily erodible valley slopes are formed on Mauch Chunk shale, sandstone, and limestone; whereas most of the valley floor is underlain by Greenbrier Limestone and shaley members of the lower Mauch Chunk (Fortney and Rentch, 2003). Other regional peatlands have formed behind a knickpoint (e.g. Cranesville Swamp), a local base level (e.g. Big Run Bog), behind alluvial levees (Darlington, 1943; Diehl and Behling, 1982; Rigg and Strausbaugh, 1949).

The floor of Canaan Valley contains one of the largest inland freshwater wetland ecosystems of peatlands, marshes, wet meadows, and shrub and forested wetlands in the eastern United States (Fortney and Rentch, 2003) (Fig. 2). CVNWR encompasses the northern portion of Canaan Valley, protecting most of West Virginia's largest wetland complex, including the five mapped peatlands totaling 246 ha. These five minerotrophic peatlands are characterized by exceptionally high biodiversity and conservation value (Byers et al., 2007), and have the largest peat deposits located in the unglaciated uplands along the Allegheny structural front in West Virginia, Maryland, and Pennsylvania (Cameron, 1970). These peatlands are ecologically classified as very poor fens, characterized as very acidic, moderately influenced by ground water, and dominated by sedges with a continuous carpet of *Sphagnum* (Kost et al., 2007). Peatlands, such as bogs and poor fens, may contain sensitive records of paleoclimate and paleoenvironment, including past moisture variations (Booth, 2010). Other peatlands are present in CVNWR and elsewhere in Canaan Valley. Unpublished soil profile descriptions for Thompson Enterprise Peat Mine as well as

Fig. 2. Landscape photograph of the peatlands located on the floor of Canaan Valley National Wildlife Refuge.

peatlands in Canaan Valley State Park, both at the southern end of the valley (Davis et al., 1999; Fedorko, 1993), indicate shallow and different horizon sequences than found for this study.

2. Methods

Old Soil Conservation Service map unit polygons, labeled as "muck and peat", provided an initial base map for this research (Losche and Beverage, 1967). Five "muck and peat" polygons were designated as Peatlands 1 through 5 for this study (Fig. 3). Soil morphology was interpreted in the field by describing 100 soil cores throughout and around the five peatlands. 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 upon the field descriptions and laboratory data, using NRCS *Soil Taxonomy* (Soil Survey Staff, 1999).

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 will vary repetitively and predictably with geomorphology, topography, and other environmental characteristics (Carlisle et al., 1998). Location of cores was representative of the immediately surrounding terrain. Local small-scale hummocks and hollows were avoided, as well as locations of known anthropogenic disturbance. GPS coordinates, location notes, surface vegetation, and geomorphology, were recorded for each soil profile.

Taking into account vegetation, ecosystem, microtopography, and water depth, a minimum of two specific core profile locations within each peatland were sampled 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 soil profile description, the second core for bulk density samples, and the third core for all other laboratory analysis. Complete core samples were collected directly from a

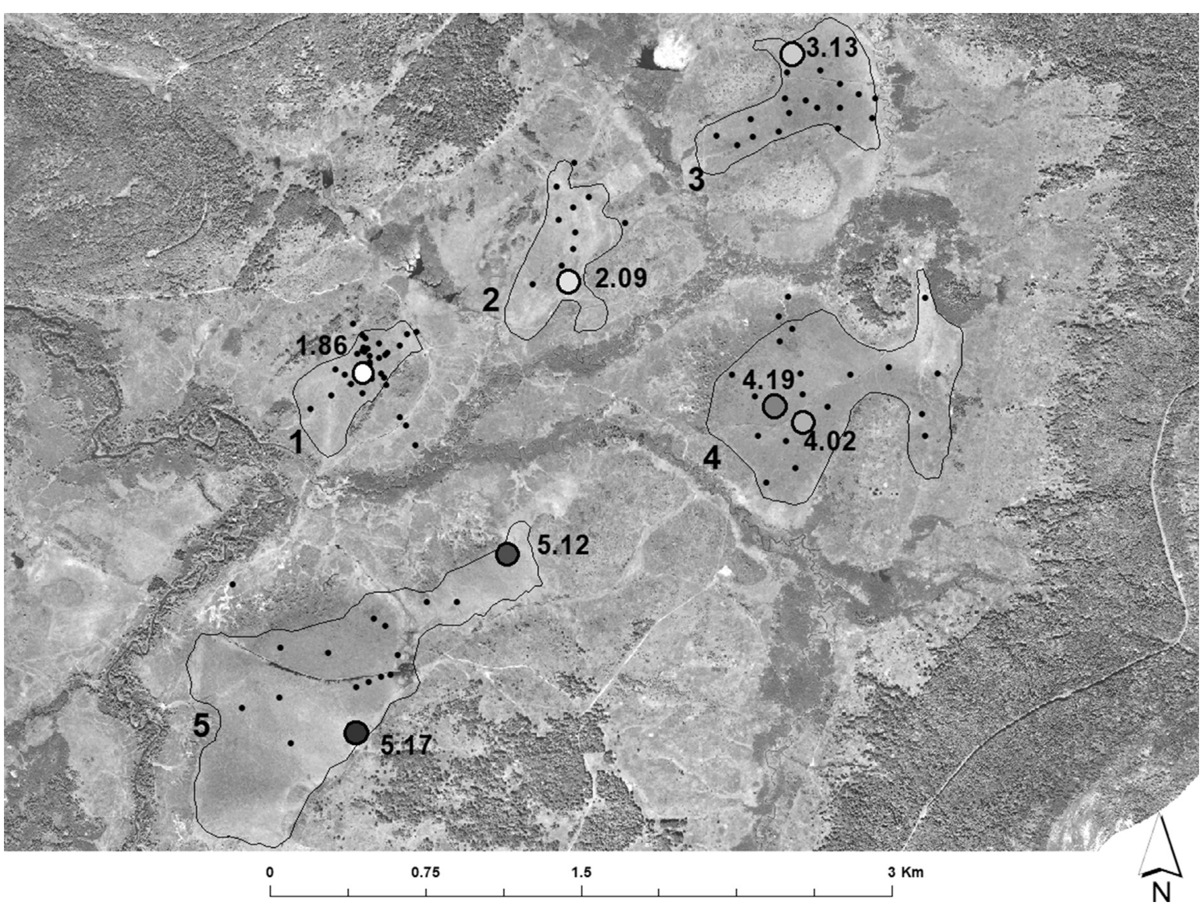

Fig. 3. Locations of 100 soil cores within and around the five studied peatlands of CVNWR. Peatlands were numbered 1 through 5 for ease of fieldwork. Cores are numbered after a decimal following each peatland number. Aerial imagery obtained from National Agriculture Inventory Program 2007 by United States Department of Agriculture.

Macaulay peat corer (a standar Russian peat borer 5 cm in diamter and 50 cm chamber length), monoliths were placed in cut-lengths of PVC tubes, wrapped with plastic, taped closed, and labeled.

Samples for radiocarbon dating were chosen and identified according to location and depth within the profile, focusing on basal peat dates, soil horizon breaks, and sedimentary sequence (Givelet et al., 2004; Piotrowska et al., 2010; Tuittila et al., 2013); 52 samples from 11 cores were dated. The lack of compaction in the upper peat profile can introduce potential bias or incorrectly boost average peat accumulation rates due to the topmost live and uncompacted section (Stivrins et al., 2017; Barber, 1981). Underlying mineral sediments were not sampled for radiocrabon dating. Upper portions of the peat profiles were sparsely sampled for radiocarbon dating as to avoid uncertainty from anthropogenic disturbance and uncertainty from proximity to live plant tissue. Samples were treated with successive washes of 1 M HCl, 1 M NaOH, and 1 M HCl at 95 °C, then rinsed twice with deionized water and dried. Bulk peat samples were graphitized in preparation for ^{14}C measurement at the Carbon, Water & Soils Lab in Houghton, Michigan. Samples were dried, weighed into quartz tubes, and sealed under vacuum. Samples were combusted at 900 °C for 6 h with cupric oxide (CuO) and silver (Ag) in sealed quartz test tubes to form CO_2 gas. The CO_2 was reduced to graphite through heating at 570 °C in the presence of hydrogen gas and an iron catalyst (Vogel et al., 1987). Graphite targets were sent to the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Lab, analyzed for radiocarbon abundance (Davis et al., 1990), and corrected for mass-dependent fractionation using an estimated $\delta^{13}C$ value of −25‰, following Stuiver and Polach (1977). Fourteen of the 52 radiocarbon samples were measured for $\delta^{13}C$ to ensure consistency with the estimated $\delta^{13}C$ value of −25‰. Measured $\delta^{13}C$ values ranged from −24.1‰ to −28.4‰, sufficiently consistent to use the estimated $\delta^{13}C$ value of −25‰. Standard radiocarbon ages were calibrated to calendar dates (cal yr BP) using OxCal 4.2 and IntCal13 Northern Hemisphere calibration curve (Bronk Ramsey, 2009; Reimer et al., 2013).

Peat accumulation rates (Table 3) were calculated as peat horizon thickness divided by the corresponding time interval in calibrated radiocarbon dated calendar years (Borren et al., 2004). IntCal13 calibrated dates and known accumulation rates were used with Bacon in R to estimate the relationship between age and depth within the cores (Blaauw and Christen, 2011). Bacon, rather than simply finding a polynomial of best fit between sampled points, uses a Bayesian approach that incorporates other information about the samples that may be available to researchers. Bayesian methods incorporate “prior” knowledge to guide the analysis in assessing final probability of occurrence. Prior information in age-depth modeling included changes in accumulation rate inferred on the basis of direct visual observation and soil profile analysis. Bacon assumes that accumulation rate is constant for a period of time and uses the prior information in combination with sampled age-depth data (e.g. radiocarbon dates from different depths) to make the most probable “wiggle matches” between sampled points which themselves contain some uncertainty (Blaauw et al., 2007). As part of the interpolation scheme, Bacon employs an autoregressive (AR) model that computes accumulation rate as a function of previous, underlying computed accumulation rates. The dependence of the model on previous values (the memory) defaulted to a reasonable value for peat soils (Blaauw and Christen, 2011). The AR model is also a function of a noise (residue) term, in this case a gamma function. This term determines the statistical distribution (probability density) of accumulation rates and determines how widely accumulation rates can differ from section to section within a core. The user-input shape factor controls the influence of user-input accumulation rate on the model. Low shape factor values allow for more variability in accumulation rates within a cored sequence. A shape factor of 2 was employed here and is generally considered reasonable for wetland ecosystems (e.g. Crann et al., 2015). Bacon simulates many runs using a self-adjusting Markov Chain Monte Carlo (MCMC) method, discarding implausible results such as negative accumulation rates. The most probable interpolation scenarios are reported (95% prediction interval depicted in gray on Fig. 4) and accumulation rates are gamma distributed after many simulated runs.

3. Results

The five NRCS “peat and muck” soil polygons, originally mapped as comprising a total of 187 ha, were re-mapped in this investigation as 246 ha. These five peatland landforms are now represented as a new NRCS soil map unit: Canaan Valley peat, moist, 0 to 3 percent slopes (map unit symbol CavA) and has been incorporated into USDA databases and mapping. Organic soil thickness in the cores within the five CVNWR peatlands ranged from 0.4 to 3.0 m; with most being less than 2.0 m. Mapping results for the five peatlands are summarized in Table 2.

Eighty-eight of the 100 soil profiles were classified as Histosols. The most representative Histosols were classified as dysic frigid Sapric Haplohemists and formally assigned a new NRCS soil series name of Canaan Valley peat with an Official Soil Series Description (Schaney et al., 2018). Silty and clayey sediments immediately underlie the peat soils in 61 of the 88 Histosol soil cores, whereas sandy sediments underlie peat soils in 12 profiled Histosols. The 12 soil cores with underlying sandy sediments varied spatially; some were near streams, some near higher elevation bedrock, and others in the center of the peatlands. No soil cores contained interbedded organic and mineral sediments that would suggest a gradual transition from open water to peatland. Underlying mineral sediment was not retrieved in 15 Histosol profiles.

Radiocarbon dating results are listed in Table 3. Forty-eight of the original 50 dates were consistent with stratigraphic order, but ages on samples CAMS-172765 and CAMS-172766 in Core 5.17 were inverted, most likely due to error at some step in the sampling or submission process. The problematic horizons in Core 5.17 were re-sampled and re-analyzed, yielding dates CAMS-174232 and CAMS-174233 that were consistent with stratigraphic order. Only age determinations on the reanalyzed samples were used for interpretation, peat accumulation rate calculation, and age-depth plots.

Each of the five CVNWR peatlands had two basal peat age determinations taken from different cores, except for Peatland 4, which had three. Four cores had only a basal peat date as shown in Table 3. Sequential radiocarbon dates were obtained for seven cores. Basal peat samples were taken from immediately above lithologic breaks from underlying mineral soil to overlying organic soil. Initiation of peat accumulation was relatively consistent throughout the five study areas with nine basal peat dates from the five peatlands ranging from ~18,600 to ~15,200 cal yr BP, during or immediately after Heinrich Stadial 1. Heinrich Stadial 1 was a timespan marked by retreat of the Lake Huron-Erie Lobe of the Laurentian Ice Sheet, which had already retreated >200 km north of its late glacial maximum position (Heath et al., 2018). The only exceptions occur in two cores from a small area in Peatland 4, where basal peat ages were ~4900 and ~4600 cal yr BP. Microtopography and hydrology of peatland surfaces and edaphic hydrology are irregular and dynamic (Ammann et al., 2013; Clymo, 1984; Holden, 2005) and were presumably the cause of two of the 11 basal peat dates being drastically younger. Core 3.13 had nine sequential radiocarbon dates that included a long interval from ~11,700 to ~5900 cal yr BP, within only 10 cm of net peat accumulation. Core 5.17 had 11 sequential radiocarbon dates that

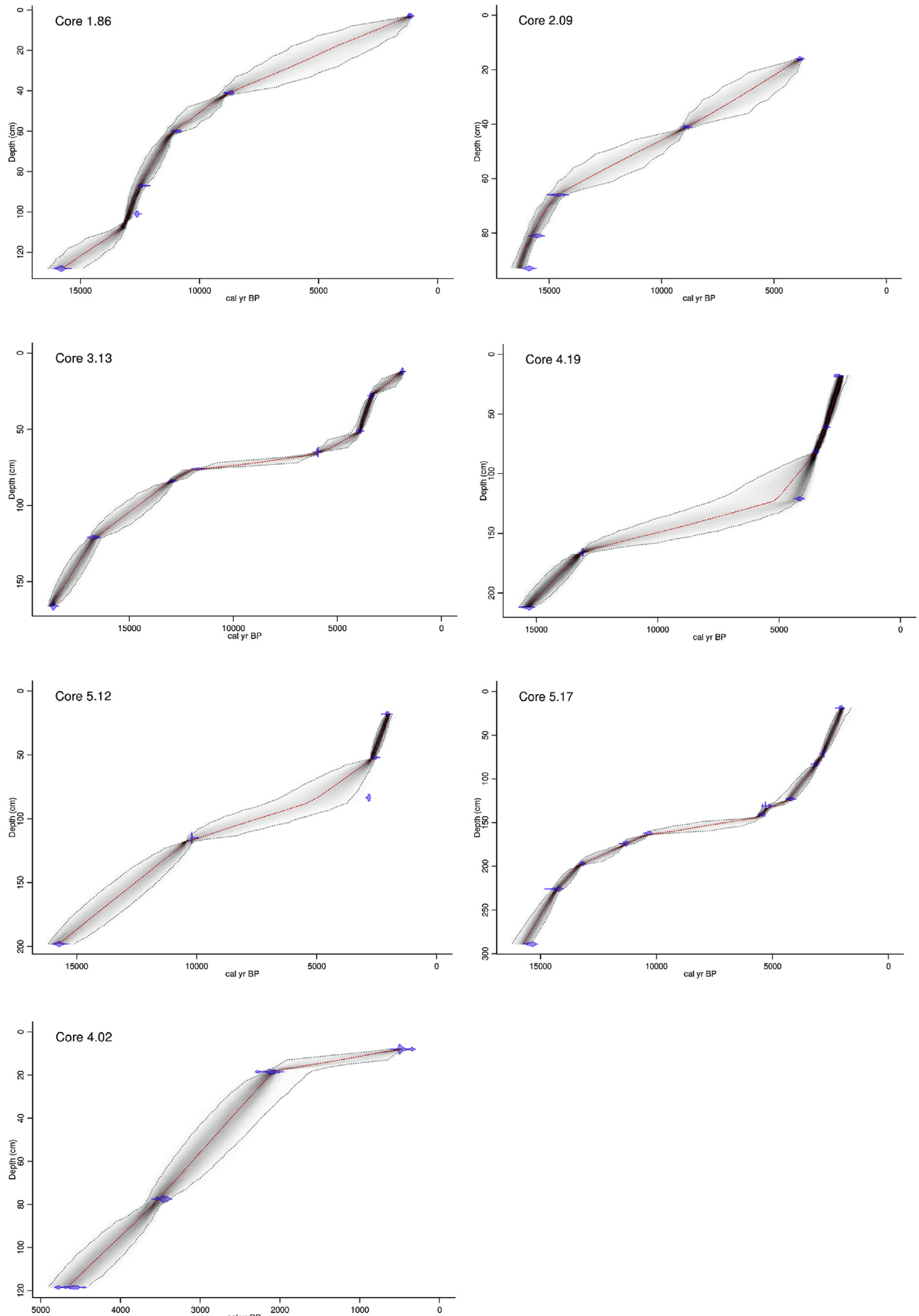

Fig. 4. Bayesian age-depth models constructed with modeling software Bacon for seven cores (Cores 1.86, 2.09, 3.13, 4.02, 4.19, 5.12, and 5.17). Note that ^{14}C dates show peat in Core 4.02 dates only from the mid-Holocene and Late Holocene. Transparent blue displays the 95% probability ranges of calibrated ages for individual ^{14}C dates. Red curve shows single 'best' model based on the weighted mean age for each depth. Gray shaded areas indicate the model's 95% probability intervals. Four temporal trends are generally distinguishable: rapid accumulation during the latest Pleistocene, lower accumulation rates in the early Holocene (Greenlandian Age), even lower accumulation rates during the mid-Holocene (Northgrippian Age), and the most rapid peat accumulation at the onset of the late Holocene (early Meghalayan Age). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

included an interval from ~10,300 to ~5400 cal yr BP, with less than 20 cm of net peat accumulation. These long intervals of very low peat accumulation in the two best-dated CVNWR Histosol cores span most of the early and middle Holocene.

Accumulation rates (Table 3) and age-depth plots of the seven sequentially dated cores displayed varied accumulation rates in response to latest Pleistocene and Holocene climatic changes (Fig. 4). 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).

Four general trends are apparent in the age-depth plots (Fig. 4) and accumulation rates (Table 3). Peat accumulation rates between ~15,800 and ~12,500 cal yr BP averaged 0.24 mm/yr. Net peat accumulation declined to a mean of 0.11 mm/yr between ~11,700 and ~8600 cal yr BP generally correlating to the early Holocene Greenlandian Age. Few radiocarbon dates were obtained on peat of mid-Holocene 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 appear to be the lowest rates 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 late Holocene 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.

4. Discussion

Motivation for this research was to reassess Allegheny Mountain peatlands by collectively using peatland development to reconstruct past climates concentrating on CVNWR. Radiocarbon dates obtained from Allegheny Mountains peatlands and trends in peat accumulation were interpreted in the context of published regional glacial chronology, paleoclimate, and paleoenvironmental literature.

During the Heinrich Stadial 2: 26,000 to 23,600 cal yr BP, glaciers advanced into Ohio and Pennsylvania (Heath et al., 2018) within 170–320 km from Allegheny Mountain peatlands in West Virginia and Maryland. Periglacial landforms caused by intense freeze-thaw activity and mass wasting occurred throughout higher elevations of the Appalachian Mountains, including the Allegheny Mountain physiographic section during the LGM (Braun, 1989; Clark and Ciolkosz, 1988; French and Millar, 2014; Ingham, 1996; Nelson et al., 2007; Whitehead, 1965). Open boreal woodlands and tundra were present along the ice margin north of 34°N, with alpine tundra in the high elevations of the Appalachian Plateau (Delcourt and Delcourt, 1986; Jackson et al., 2000; Whitehead, 1973). Boreal cool-temperature conifers dominated vegetation south of the glacial limit to 33°N (Jackson et al., 2000; Whitehead, 1965, 1967; 1973; Yann et al., 2013). The mid-Atlantic region had forests ranging from cold temperate mixed conifer-hardwood to high boreal in character (Litwin et al., 2013). Sirkin (1977) found tundra vegetation was prevalent throughout the Delmarva Peninsula until 18,000 cal yr BP. Leigh (2008) found that cold and dry conditions with savanna vegetation existed in the southeastern United States coastal plain from 30,000 to 16,000 cal yr BP. High fire activity in central Tennessee coincided with the dominance of cool-temperature conifers from the Last Glacial Maximum (LGM) until 15,000 cal yr BP (Ballard et al., 2016).

As permafrost in the Allegheny Mountain section began to melt from 20,000 to 18,000 cal yr BP (French and Millar, 2014), tundra and alpine tundra vegetation retreated north and the colluvial geomorphic regime that dominated the tundra transitioned into a fluvial geomorphic regime (Delcourt and Delcourt, 1986). Basal peat dates from CVNWR, including ~18,700 and ~18,200 cal yr BP (Table 3), are the oldest published dates for peat initiation in the Allegheny Mountain section. CVNWR cores revealed no transitional interbedded organic and mineral sediments indicative of an emergent marsh wetland phase. Larabee (1986) dated a sediment sequence interpreted as evidence that Big Run Bog began as an open body of water that transitioned first into a wetland accumulating mineral sediments and later evolved into a peatland (Table 1). Maxwell and Davis (1972) dated mineral limnic sediments underlying peat at Buckles Bog, followed by clayey gyttja (Table 1) also interpreted as evidence of open water that transitioned into a emergent marsh type wetland. As a result of immature and transitioning integrated drainages (Halsey et al., 2000) and an increase in available water (Morris et al., 2018), the landscape was stabilizing and favored the initiation of peatland development during 20,000 to 18,000 cal yr BP.

The climate of the northeastern United States and the Appalachian region ameliorated to warmer conditions around 14,000 cal yr BP (Delcourt and Delcourt, 1986; Kneller and Peteet, 1993), roughly coinciding with the warm and moist Bølling-Allerød interstadial, from 14,500 to 12,600 cal yr BP (Williams et al., 2011; Yu, 2007). The warming and moistening climatic trend correlates with moderately high peat accumulation rates in CVNWR from ~15,800 to ~12,500 cal yr BP. Both Larabee (1986) at Big Run Bog and Maxwell and Davis (1972) at Buckles Bog show not only peat initiation, but also the most rapid peat accumulation during this interval. Watts (1979) dated organic clay from Cranberry Glades ~14,100 cal yr BP (Table 1), as this ecosystem transitioned into an emergent marsh type wetland. Halsey et al. (2000) identified that the majority of peat accumulation in central Appalachians occurred during this time interval.

The Bølling-Allerød interstadial was followed by the Younger Dryas stadial, a cold period from 12,600 to 11,700 cal yr BP (Miller and Gingerich, 2013; Webb et al., 1993; Williams et al., 2011). The Younger Dryas saw significant vegetation changes throughout the eastern United States (Shuman et al., 2002). Webb et al. (1993), studying pollen assemblages in the northeastern United States, concluded that the low annual precipitation, but high soil moisture around 12,000 cal yr BP, suggested cold temperatures correlating with the Younger Dryas. Radiocarbon dating at CVNWR, may not have been at a fine-enough resolution to detect the Younger Dryas; peat ages in CVNWR Core 3.13 from 12,960 to 11,687 cal yr BP show a very low accumulation rate of 0.06 mm/yr (Table 3). Larabee (1986) and Maxwell and Davis (1972) both report fibrous organic clay ~12,600 cal yr BP, and fibrous peat ~12,400 cal yr BP, respectively, dating to this period (Table 1). It is unclear if Younger Dryas cold temperatures affected peatland development, as moisture balance is more essential than temperature in peat accumulation (Evans and Warburton, 2010; Loisel and Garneau, 2010; Vitt, 2006).

The Holocene Epoch, which began 11,700 cal yr BP, is an interglacial period with numerous smaller climatic fluctuations (Hou et al., 2011; Li et al., 2007; Webb III et al., 1998; Willard et al., 2005). The early Holocene Greenlandian Age, defined as 11,700 to 8236 cal yr BP (Cohen et al., 2013; Head and Gibbard, 2015; Walker et al., 2012, 2018), was characterized in the eastern United States as a cool and dry period (Stinchcomb et al., 2012; Zhao et al., 2010) with an available moisture at a postglacial minimum around 9000 cal yr BP (Li et al., 2007; Stinchcomb et al., 2012, 2013; Webb et al., 1993; Willard et al., 2005). The Greenlandian Age closely correlates with modest peat accumulation rates in CVNWR from

Table 2
Mapping results for the 100 soil cores in and around the five CVNWR peatlands.

Peatland #	Originally mapped as	Remapped as	Number of cores	Average peat thickness	Maximum peat thickness
Peatland 1	9 ha	18 ha	32	~100 cm	174 cm
Peatland 2	26 ha	26 ha	11	~95 cm	170 cm
Peatland 3	21 ha	32 ha	19	~125 cm	170 cm
Peatland 4	71 ha	69 ha	21	~130 cm	217 cm
Peatland 5	60 ha	101 ha	17	~170 cm	296 cm

Table 3
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 a peat accumulation rates which were used for data interpretation.

Laboratory ID	Sample #	Core #	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	12810	40	15449	15109	15258	
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	11128	10774	10928	0.18
CAMS-172763	39	1.86	86–88	10475	35	12560	12147	12451	0.82$_+$
CAMS-172764	40	1.86	100–102	10635	30	12690	12559	12621	0.08$_+$
CAMS-171738	21	1.86	127–129	13155	40	16002	15637	15807	
CAMS-171739	22	2.05	119–121	15045	40	18435	18099	18284	
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	12455	45	14961	14251	14598	0.16
CAMS-172759	35	2.09	80–82	12985	40	15732	15315	15528	0.33
CAMS-171737	20	2.09	92–94	13225	40	16069	15730	15896	
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	10095	40	11954	11404	11687	0.06
CAMS-172753	29	3.13	83–85	11085	35	13063	12824	12960	0.20
CAMS-170484	12	3.13	94–96	11680	30	13570	13445	13510	0.08
CAMS-172754	30	3.13	120–122	13815	40	16946	16488	16715	0.23
CAMS-170485	13	3.13	165–167	15375	35	18759	18544	18653	
CAMS-171740	23	3.14	121–123	13870	40	17009	16573	16802	
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	11235	35	13164	13041	13097	0.21
CAMS-171741	24	4.19	211–213	12850	40	15545	15160	15315	
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	10235	10170	10204	0.15
CAMS-170477	5	5.12	197–199	13105	35	15940	15540	15733	
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	10483	10231	10323	0.12
CAMS-172769	45	5.17	173–175	9930	30	11590	11241	11312	0.12
CAMS-171735	18	5.17	196–198	11360	35	13290	13115	13203	0.28
CAMS-171734	17	5.17	225–227	12310	35	14531	14075	14237	0.55
CAMS-171731	14	5.17	288–290	12890	40	15598	15210	15382	

~11,600 to ~8600 cal yr BP. Kneller and Peteet (1993), at Brown's Pond, Virginia, found low water levels indicating dryer conditions between 10,000 and 8000 cal yr BP. The end of Greenlandian Age was marked by a pronounced millennial scale cold event at 8236 cal yr BP (Daley et al., 2016; Head and Gibbard, 2015; Hu et al., 1999; Mayewski et al., 2004; Viau et al., 2006; Walker et al., 2012, 2018; Wanner et al., 2015; Willard et al., 2005). Known as the 8.2 event, this cold event was most likely a result of sudden drainage from glacial lakes Agassiz and Ojibway into the North Atlantic; this freshwater forcing was a catalyst for the abrupt climate change (Walker et al., 2018).

The mid-Holocene Northgrippian Age, defined as 8236 to 4250 cal yr BP (Cohen et al., 2013; Head and Gibbard, 2015; Walker et al., 2012, 2018), was characterized in eastern North America as a complex and dynamic climatic interval interposed with numerous regional droughts (Newby et al., 2014; Shuman and Marsicek, 2016; Stinchcomb et al., 2013; Viau et al., 2006), including a drought 5500 cal yr BP that coincided with a widespread *Tsuga canadensis* decline (Booth et al., 2012; Delcourt and Delcourt, 1986; Williams et al., 2011; Zhao et al., 2010). Eastern North America generally experienced a rise in temperature culminating with mid-Holocene Climatic Optimum, during which temperatures were considerably warmer than today (Beget, 1983; Driese et al., 2005; Fairbridge, 1982; Mullins et al., 2011; Springer et al., 2009; Wanner et al., 2015). The exact timing of the Climatic Optimum varied from region to region as did the coinciding abundance of available moisture (Barber et al., 1999; Clarke et al., 2003; Shuman and Marsicek, 2016; Viau et al., 2006; Zhao et al., 2010).

Extremely low accumulation rates from CVNWR are consistent with very dry mid-Holocene climatic conditions. Research in central New York and eastern Lake Ontario indicate the overall-climate during the Climatic Optimum was generally warm and wet (McFadden et al., 2005; Mullins et al., 2011), whereas studies in eastern Pennsylvania, North Carolina, and Tennessee suggest warm and dry conditions (Ballard et al., 2016; Driese et al., 2008; Stinchcomb et al., 2013; Tanner et al., 2015). Webb at al. (1993) found slight increases in soil moisture and precipitation at 6000 cal yr BP in the northeastern United States.

The Climatic Optimum has been identified previously in the central Appalachians. Watts (1979) found that late Quaternary vegetation of the central Appalachians indicated Climatic Optimum water tables were lower or less stable than today. Springer et al. (2009) found evidence of a warm Climatic Optimum in southeastern West Virginia while investigating stable isotopes in stalagmites and clastic cave sediments. Also working in southeastern West Virginia, Driese et al. (2005) found mid-Holocene warmer, dryer, climatic conditions weathered previously deposited fluvial gravel deposits. Cameron (1970) in Canaan Valley, Larabee (1986) in Big Run Bog, and Watts (1979) in Cranberry Glades all have recorded dates from this period; however, their dating resolution is not fine enough to determine accumulation rates and their varied soil profile descriptions did not follow soil science terminology to allow exact correlation. The Northgrippian Age ended with a pronounced climatic event at 4250 cal yr BP which manifested in the mid-continent of North America as a widespread and severe drought (Booth et al., 2005; Shuman and Marsicek, 2016; Walker et al., 2012, 2018; Williams et al., 2011).

The late Holocene Meghalayan Age, from 4250 cal yr BP to present (Head and Gibbard, 2015; Walker et al., 2012, 2018) brought wet conditions to the eastern United States (Willard et al., 2005), with minor climatic fluctuations including intermittent droughts, the Medieval Warming Period, and the Little Ice Age (Li et al., 2007; Newby et al., 2014; Shuman and Marsicek, 2016; Stinchcomb et al., 2013; Willard et al., 2005). Age-depth plots and the accumulation rates at CVNWR show rapid peat accumulation in the early Meghalayan Age, concurring with wet conditions. However, peat accumulation slowed in the late Meghalayan Age of CVNWR. Cameron's (1970) one radiocarbon date from CVNWR indicates an accumulation rate of 0.22 mm/yr for the late Holocene. Booth et al. (2016) working on a single core in Cranesville Swamp dated peat accumulation beginning at ~1000 cal yr BP. Larabee (1986) in Big Run Bog dated fibrous organic clay from the late Meghalayan Age. Although coarsely dated, overall Meghalayan Age, Allegheny Mountain peatland records do conform to the generally wet conditions for eastern United States regional paleoclimate reported by others.

5. Conclusions

Understanding peatland stratigraphy and development history is crucial to paleoclimatic reconstruction (Ovenden, 1990; Zhang et al., 2016). Extensive fieldwork coupled with high-resolution dating of peat stratigraphy provides the thorough baseline necessary for an understanding of variations and similarities among Allegheny Mountain peatlands. The quantity of complete soil profile descriptions as well as dated cores from CVNWR allows this ecosystem to inform peatland development history more fully than previous studies of peatlands in the region, particularly because previously published cores are very difficult to interpret with certainty because profile descriptions terminology varied greatly from study to study. Paleoenvironments interpreted from any one of the soil cores in this study could be considerably different from an interpretation based upon a comprehensive integration of the compiled history of peat development (Ovenden, 1990; Zhang et al., 2016).

Future peat research in the region should follow standard NRCS soil-profile description procedures and taxonomic classifications to ensure consistency of interpretation. Variable peat stratigraphy and peat accumulation rates require the analysis of multiple cores within well-constrained peatlands to avoid paleoclimatic interpretations skewed from individual peat cores that may be atypical of peatland-wide stratigraphy and regional events (Ovenden, 1990; Zhang et al., 2016).

Credit author statement

Mitzy L. Schaney: Conceptualization, Investigation, Writing - Original Draft, Project administration; J. Steven Kite: Writing - Review & Editing, Supervision, Validation; Katherine Heckman: Resources, Data Curation; Christopher Coughenour: Resources, Data Curation, Formal analysis; Christopher R. Schaney: Visualization.

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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