Quaternary Science Reviews 228 (2020) 106104

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A late Holocene subfossil Atlantic white cedar tree-ring chronology from the northeastern United States

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A R T I C L E I N F O

Article history:
Received 8 September 2019
Received in revised form
22 November 2019
Accepted 22 November 2019
Available online 10 December 2019

Keywords:
Tree-rings
Radiogenic isotopes
North America
Paleoclimatology
Holocene
Geomorphology
Coastal

A B S T R A C T

Tree-rings provide precise annually dated climate information, but their application can be limited by the relatively short lifespan of many trees. To overcome this limitation, tree-ring records can be extended over longer time periods by connecting living trees with older “sub-fossil” trees, which can provide information on longer timescales throughout the Holocene. These long chronologies are proxy records of past climate, provide precise chronological information for extreme events, and give insight into the range of natural climate variability prior to the instrumental period. In the densely populated northeastern United States, few tree-ring records are longer than 500 years, and there are no millennial-length tree-ring chronologies for the region. Here, we use a combination of standard dendrochronological and radiocarbon techniques, including use of the 774 CE radiocarbon excursion, to generate an absolutely dated 2500 year-long tree ring record from living, archaeological, and subfossil Atlantic white cedar (*Chamaecyparis thyoides*) found in the coastal northeastern United States. Our chronology demonstrates the potential to develop multi-millennial *Chamaecyparis thyoides* tree-ring records to address previously unanswered questions regarding late Holocene hydroclimate, extreme events, and temperature variability in New England.

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1. Introduction

Tree rings provide high-resolution information about past environmental conditions that can be used to interpret climate variability, ecological change, and human history. Although there are a few exceptionally long-lived (thousands of years) species (Douglass, 1919; Ferguson and Graybill, 1983; Stuiver et al., 1986; Lara and Villalba, 1993; Salzer and Hughes, 2007; Stahle et al., 2019), most tree-ring records based on living trees are relatively short and are limited to the past several hundred years. To extend tree-ring chronologies over longer periods, pieces of wood from older dead trees must be collected and precisely appended to the living tree record. Environments which are very dry, very cold, or in which the wood is submerged (and thereby prevented from decaying) can preserve the wood of trees which died hundreds or thousands of years ago. Such material is termed ‘subfossil’ wood (old and preserved wood, but not mineralized as with true fossilization) and has been used to extend tree-ring chronologies over the span of the Holocene (Ferguson and Graybill, 1983; Stuiver et al., 1986; Becker, 1993; Hughes and Graumlich, 1996; Grudd et al., 2002; Friedrich et al., 2004; Stambaugh and Guyette, 2009; Nicolussi et al., 2009; Shao et al., 2010; Hessl et al., 2018). Multi-millennial length tree-ring chronologies provide fundamental information for a diversity of scientific disciplines, including high-

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https://doi.org/10.1016/j.quascirev.2019.106104
0277-3791/Published by Elsevier Ltd.

resolution paleoclimate reconstructions (Eckstein et al., 2009; Boswijk et al., 2014; Stambaugh et al., 2011; Hessl et al., 2018), the development of the Holocene portion of the International Radiocarbon Calibration Curve (Reimer et al., 2013), archaeological and geological dating (Baillie, 2014; Oppenheimer et al., 2017; Pearson et al., 2018), and the spatial and temporal characterization of local, regional, and global scale events (c.f. Salzer and Hughes, 2007; Helama et al., 2019). The northeastern United States (the 'Northeast'), a region encompassing the states of New Jersey and New York north to the state of Maine, is home to over sixty-four million people, including the cultural and economic centers of Boston, Providence, New Haven, and New York City. This region is faced with elevated rates of sea level rise (Goddard, 2014; Kemp et al., 2017) and is currently experiencing the fastest temperature and hydroclimate changes in the lower 48 continental United States (Griffiths and Bradley, 2007; Horton et al., 2014; Karmalkar and Bradley, 2017). The Northeast has few multi-century length tree-ring records, and no millennial-length records archived on the International Tree Ring Data Bank (St. George, 2014). Thus, there are limited high-resolution climate data from this densely-populated region that can be used to inform studies of current and predicted climate change by helping to understand radiative forcing, internal variability, and extreme events (Marlon et al., 2017).

The longest-lived species in North America, including bristlecone pine (*Pinus longaeva*, D.K.Bailey), are found in western North America. The longest tree-ring records in eastern North America come from Canada (c.f. Buckley et al., 2004, 2787 years) or the southeastern United States (c.f. Stahle et al., 2019, 2624 years). While some northeastern tree species are long-lived, such as cliff-dwelling northern white cedar (*Thuja occidentalis*, L.) (Hofmeyer et al., 2009), and eastern red cedar (Juniperus virginiana, L.) (Guyette et al., 1982; D'Arrigo et al., 2012; Maxwell et al., 2012), neither northern white cedar nor eastern red cedar tree-ring widths are strongly correlated with climate in the northeast, which limits their utility for growth based climate reconstructions using the ring-width proxy (Pederson et al., 2013; Marlon et al., 2017). Thus, existing northeastern tree-ring records contribute relatively little information to our understanding of late Holocene climate variability or ecological change, as paleoclimatic reconstructions in the region are limited by both the availability of suitable species and the longevity of the local species. The regional topography does, however, offer potential for the preservation of sub-fossil wood in the form of anaerobic wetlands and marshes. The utility and potential climate sensitivity of subfossil species from these environments has not yet been fully explored, but the development of new, long sub-fossil chronologies holds the potential to explore aspects of past climate, extreme events, ecology, and hydrology, through development of a range of proxies based on ring width, wood density, wood anatomy, or stable isotope analysis.

One northeastern species that demonstrates high potential for long tree-ring sequence construction is Atlantic white cedar (*Chamaecyparis thyoides*, (L.) BSP; 'AWC'). AWC, a protected, wetland conifer, is in the northernmost extent of its range in the Northeast, and is rarely found more than 200 km from the coast (Laderman, 1989; Little and Garrett, 1990; Gengarelly and Lee, 2006). AWC was harvested commercially for shingles, barrel, and boat construction through the 19th century due to its decay resistant properties (Little and Garrett, 1990). This resistance also facilitates the preservation of subfossil wood buried in sediments, below saltmarsh turf, and in inter-tidal environments for thousands of years (Bartlett, 1909; Heusser, 1949; Gleba, 1978; Laderman, 1989). Extensive harvesting of the species since the early 17th century limits the ages of modern living AWC chronologies to the late 18th century (Hopton and Pederson, 2005; Pearl et al., 2017). Investigations of the climate sensitivity of the species have shown that AWC ring width is significantly correlated with regional temperatures (Hopton and Pederson, 2005; Pearl et al., 2017), and local hydroclimate in certain coastal geological settings (Pearl et al., in revision at *Journal of Geophysical Research*). The physical hardiness and climate sensitivity of AWC in the northern extent of its range makes it an optimal species to target for paleoclimate applications.

The existence of preserved AWC in northeastern tidal or submerged environments has been known for over a century (Cook, 1857; Bartlett, 1909; Heusser, 1949), yet a continuous chronology that connect subfossil and modern trees has never been generated from these sites. Here, we use both standard dendrochronological cross-dating techniques (Douglass, 1941; Fritts, 1976) and high precision radiocarbon measurements (Ramsey et al., 2001; Kromer, 2009) to develop precise chronological control for ring-width time series at three subfossil AWC sites along the Northeast coast (Fig. 1). We also use a well-documented global ^{14}C marker event at 774–775 CE from an extreme solar proton event (Miyake et al., 2012, 2013; Jull et al., 2014; Güttler et al., 2015; Mekhaldi et al., 2015; Rakowski et al., 2015; Ohare, 2017; Sukhodolov et al., 2017) to securely fix the date of one of these sites and anchor our region subfossil chronology precisely within the Common Era.

2. Methods

2.1. Study sites and sample collection

2.1.1. Southern New Jersey archaeological wood

Our southern New Jersey living AWC tree-ring chronology extends back to the late 1760s (Pearl et al., 2019). This master chronology was recently extended to 1644 CE using over 100 samples preserved at historic and archaeological sites. Specifically, beams from 16 granaries, barns, and cabins across southern New Jersey (Cook and Callahan, 2017) ('HIS', Fig. 1). We used this longer updated southern New Jersey master chronology to cross-date with sub-fossil tree-ring-width sequences from a range of sites in this part of the species range (see Fig. 1).

2.1.2. Meadowlands collection

An ancient, well preserved, AWC forest was rediscovered, mapped by diameter class, and sampled with chainsaws in 1999 in the Hackensack Meadowlands, New Jersey ('MDW', 39.357°N −75.34°W, Fig. 1) (Zimmermann and Mylecraine, 2000). Local pollen records show large scale ecosystem transitions in post-glacial Meadowlands. The *Alnus* and *Fraxinus* dominated forest transitioned to a primarily *Picea* and *Larix* landscape before the region transitioned to wetland and AWC dominated the canopy in the Common Era (Heusser, 1963; Zimmermann and Mylecraine, 2000). Early Dutch settlers in the mid 1600s cleared the AWC swamp and drained the land to establish extensive saltmarsh (*Scirpus*) meadows, although peripheral AWC persisted in the Meadowlands until the early 1800s (Marshall, 2004). After centuries of anthropogenic hydrological and ecological manipulations the tidal flow now extends much further into the wetlands, transforming them into a brackish and saltwater habitats (Marshall, 2004). The area is, therefore, no longer suitable for the species due to the salinity of the surface and ground water (Harshberger and Burns, 1919; Heusser, 1949; Sipple, 1971). The Meadowlands collection contains the largest and longest lived AWC cross sections from any of the sampled subfossil sites, with rooted stumps nearly 150 cm in diameter. These samples were transported to the Harvard Forest in 2015 for analysis and archiving. Multiple sections from 13 well-preserved specimens were used in this study.

2.1.3. Hundred Acre Cove, RI

Hundred Ace Cove ('HAC', 41.76°N −71.31°W, Fig. 1) is the third

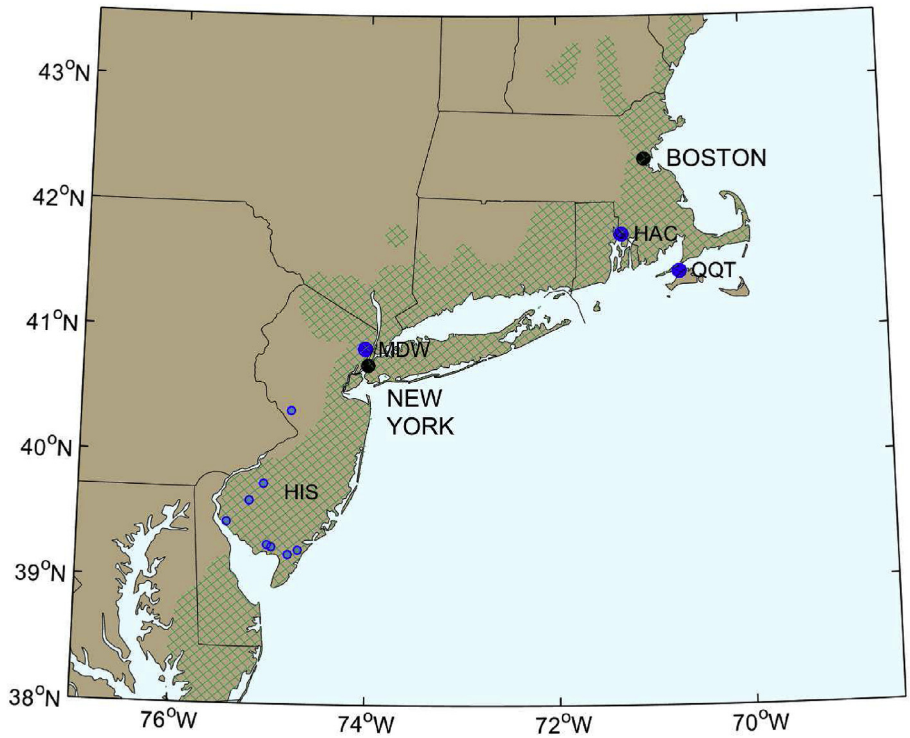

Fig. 1. Northeastern United States subfossil Atlantic white cedar site locations used in this study. Large blue circles indicate the location of the subfossil Atlantic white cedar sites in this study. Smaller, lighter blue circles indicate the location of the historical/archaeological sites in New Jersey ('HIS') that are used in the Southern New Jersey master chronology. 'MDW' = Meadowlands site, 'HAC' = Hundred Acre Cove, and 'QQT' = Quamquissett. Green hatching indicates the species distribution as defined by the United States Forest Service (Little, 1978). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

largest saltmarsh estuary in Rhode Island (US Fish and Wildlife Service, 1991). The estuary covers over 1.75 km^2, and is almost 50% open water (US Fish and Wildlife Service, 1991). The salt-marshes are dominated by cordgrasses (*Spartina alterniflora* and *Spartin patens*), and contain large permanent non-tidal ponds. The marshes abut extensive mud flats where subfossil stumps and trunks are partially exposed at low tide. All samples were taken within 40 m of the saltmarsh, as deep muds at low tide and high water in the marsh channels hindered more extensive sampling. Fifty-three subfossil AWC and 19 subfossil pitch pine (*Pinus rigida* Mill.) cross-sections and wedges were collected at low tide using handsaws and chainsaws. Subfossil AWC was distinguished from the subfossil pine samples by both its macroscopic and microscopic wood anatomy, including AWC's lack of resin ducts, its small and uniform latewood, and homogeneous medullary rays (Schweingruber, 1978). Many samples were partially decomposed or damaged by accreted marine fauna, such as bivalves and crustaceans, that had colonized and burrowed into the subfossil wood. Sample locations were recorded using a GPS, labeled, and wrapped in plastic for transport. Due the fragile nature of the samples, we rinsed, removed any attached macro-organisms, and photographed the subfossil samples before storing them in a 4 °C fridge. By keeping the samples in this cold and humid environment, we prolonged the drying process to discourage rapid pressure release in the cross-sections that may result in breakage along ring boundaries. Samples that were fragile or broken were mounted on plywood before the samples were sanded with progressively finer grit to reveal fine wood anatomical structure.

2.1.4. Quamquissett, MA

Quamquissett is a small (less than 0.01 km^2), shallow, tidal inlet, backed by a semi-enclosed saltmarsh currently dominated by *Phragmites australis* located on the Buzzards Bay side of Woods Hole, Massachusetts ('QQT', 41.537°N −70.661°W, Fig. 1). AWC peat below the saltmarsh vegetation indicates that both the inlet and saltmarsh were previously AWC forests, with subfossil AWC stems and stumps exposed at low tide in the tidal inlet (Bartlett, 1909). The abrupt steep topographic transition of 2–4 m between Quamquissett and the surrounding coast are characteristic of an ancient kettle hole environment (Bennett and Glasser, 2011). Although modern AWC rarely reach more than 200 years old, cedar wetlands have dominated these ombrotrophic ecosystems in Cape Cod for more than a millennium (Motzkin et al., 1993). This paleoforest appears to have been a homogeneous stand of AWC, with only a few trunks of modern pine or oak remnants integrated with AWC stumps and stems along the periphery. We collected 28 well-preserved subfossil AWC cross sections and wedges from throughout the inlet using handsaws and chainsaws at low tide. In general, Quamquissett samples were less fragile than Hundred Acre Cove specimens, but most samples were missing their bark and outer rings due to tidal abrasion and the action of marine fauna. Sample locations were recorded using a GPS before samples were labeled and processed in the same manner described in section 2.1.3.

2.2. Conventional ^{14}C measurements and site chronology development

Small sections between 1 and 10 rings of each AWC sample were removed from the outer edge and, if possible, the inner portion of each sample for radiocarbon dating. The exact number of years was recorded between these samples. Samples were pre-treated using a modified Acid-Base-Acid method to remove non-structural carbon and extract cellulose (De Vries and Barendsen, 1954; Gaylord et al., 2019). We used a combination of a low precision 'reconnaissance' analysis method (Roberts et al., 2010, 2011; McIntyre et al., 2011, 2013; Sookdeo et al., 2017), and traditional high-precision radiocarbon dating methods (Longworth et al., 2015) at the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS) facility at Woods Hole Oceanographic Institution. The reconnaissance analysis was performed after initial sample collection in order to obtain approximate estimates of age. This method combusts the pre-treated wood in an elemental analyzer (Elemental vario EL cube) and the resulting CO_2 is expanded into a 7 mL septa-sealed glass vial. The vials are processed via a modified Gilson® GX-271 Liquid Handler and the CO_2 is carried directly into the continuous flow accelerator mass spectrometer (CFAMS) at NOSAMS (Roberts et al., 2010, 2011; McIntyre et al., 2011). Traditional, high precision dating was performed on Hundred Acre Cove and Quamquissett samples for increased dating confidence of the mixed age sites. This method combusts pre-treated samples to CO_2, and then converts the samples to graphite using standard closed tube graphite procedures (Xu et al., 2007; Burke et al., 2010), before the graphite powders are pressed into aluminum targets and run on the AMS at NOSAMS (Longworth et al., 2015). Samples were normalized to OX-II (Stuiver, 1983), secondary standards (IAEA C-3, FIRI-F, and FIRI-H), and radiocarbon-free acetanilide (J.T. Baker, A068-03) was used for blank correction. Radiocarbon results were calibrated for secular changes in atmospheric radiocarbon concentrations using the International Radiocarbon Calibration Curve (IntCal13) (Reimer et al., 2013). For samples with both and inner and outer radiocarbon dates, we decreased the uncertainty of the individual calibrated radiocarbon ages by including in our age model the known number of years from the annual rings between the two radiocarbon dates against the IntCal13 radiocarbon curve using the program OXCAL (Ramsey et al., 2001; Galimberti et al., 2004).

We took one or two representative radii of all Quamquissett and Hundred Acre Cove samples, and measured the ring width at 0.001 mm precision. The large and often complete cross sections of the Meadowlands collection allowed us to take measurements of 2–3 radii of many samples, which increased replication for site crossdating. For each site we identified co-temporal AWC cohorts based on their calibrated radiocarbon age ranges (Stambaugh and Guyette, 2009). We then visually cross-dated the specimens within their age-defined cohorts (Stokes and Smiley, 1968; Yamaguchi, 1990) (Fig. 2), and statistically confirmed the cross dating using the program COFECHA (Holmes, 1983). We used the interseries correlation metric to evaluate the cross-dating agreement at each site (Wigley, 1984). When a compilation of similarly aged tree ring series reached a significant interseries correlation ($p < 0.01$) (Holmes, 1983), we tested the stability of statistical results and determined alternative dating possibilities by iteratively taking each series out of the temporary master chronology and performing a correlation analysis with that series as 'undated' using the program COFECHA (Holmes, 1983; Stambaugh and Guyette, 2009). The chronologies were further tested for dating accuracy by matching the sample's relative placement in the chronology to its possible age distribution along the IntCal13 curve (Reimer et al., 2013) using the program OxCal (Ramsey et al., 2001). We analyzed the spectral and autocorrelation properties of the resulting chronologies to potentially distinguish their paleolandscapes and climate sensitivity.

2.3. Annual ^{14}C measurements

A rapid excursion of approximately 12‰ in atmospheric $\Delta^{14}C$ between 774 and 775 CE has now been identified worldwide in the cellulose of annual tree rings formed at that time (Miyake et al., 2012, 2013; Jull et al., 2014; Güttler et al., 2015; Mekhaldi et al., 2015; Rakowski et al., 2015; Sukhodolov et al., 2017; Büntgen et al., 2018). This global ^{14}C marker has already been used as an

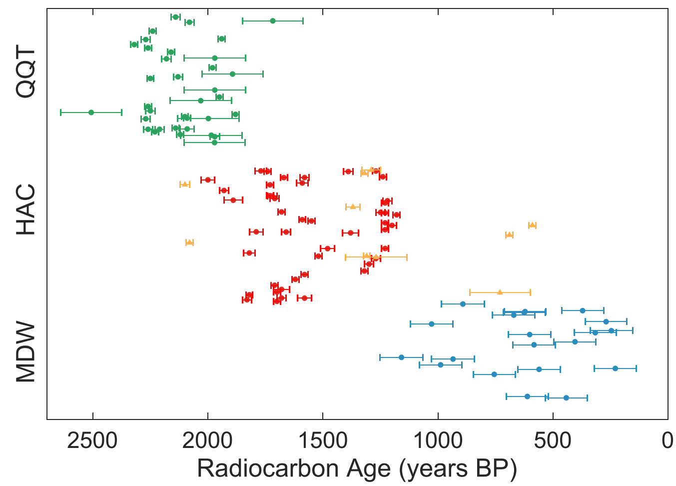

Fig. 2. Radiocarbon ages ('years BP' as defined by Stuiver et al. (1986)) of samples in this study. Meadowlands AWC dates are indicated by blue circles, Hundred Acre Cove AWC by red circles, Hundred Acre Cove pine by orange triangles (oldest pine not shown), and Quamquissett AWC by green circles. Error bars indicate radiocarbon age uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

effective and absolute geochronological tie-point (c.f. Wacker et al., 2014; Sigl et al., 2015; Oppenheimer et al., 2017; Hakozaki et al., 2018). Following conventional radiocarbon dating of Hundred Acre Cove samples, we determined that the floating chronology must include the atmospheric 774–775 CE ^{14}C excursion, and that if we could locate it exactly it could be used to secure this floating segment of the chronology exactly in time. We identified the years spanning the approximate period of the event within the previously defined calibration ranges. We then dissected the years dated to approximately 734 through 754 CE and measured the ^{14}C of each individual year. Values were converted to $\Delta^{14}C$ Stuiver and Polach (1977) using equation (1):

$$\Delta^{14}C = \left[Fm * e^{\lambda(1950 - Y_c)} - 1\right] * 1000 \quad (1)$$

Where Fm is the fraction modern and Y_c is the absolutely dated year. We changed our estimate of Y_c based on our dendrochronological dating until the large jump in $\Delta^{14}C$ was synchronous with that of a number of securely dated northern hemisphere tree-ring $\Delta^{14}C$ records covering the years 773–774 CE (Büntgen et al., 2018). Although the 774 CE cosmogenic radiocarbon event is globally coeval, there are latitudinal differences in the magnitude of the excursion in tree-ring records (Jull et al., 2008; Büntgen et al., 2018). We focused our $\Delta^{14}C$ comparison on absolutely dated records from Albania (Seim et al., 2012), Oregon (Clark et al., 2017), and Greece (Klippel et al., 2017) as they are located at the most similar latitudes to Hundred Acre Cove. These comparisons allow us to precisely date the radiocarbon excursion and lock the Hundred Acre Cove chronology to exact calendar years.

2.4. Multi-millennial chronology development

Where the individual site chronologies overlapped with each other within radiocarbon uncertainty, we visually and statistically cross-dated both the site master chronology and individual series against those of the other site using standard dendrochronological techniques (Stokes, 1996) and the program COFECHA (Holmes, 1983). We adjusted the Meadowlands chronology up to a maximum of ± 50 years (the modelled uncertainty in

Meadowlands's radiocarbon ages, Fig. 3) and the Quamquissett chronology up to a maximum of ± 13 years (the modelled uncertainty in Quamquissett's radiocarbon ages, Fig. 7) against the two absolutely dated series (Historical and Hundred Acre Cove) to determine the best fit of ring-width patterns within the radiocarbon constraints modelled by matching all radiocarbon dates in the chronology against their possible position on the IntCal13 curve (Figs. 3 and 7) (Ramsey et al., 2001; Galimberti et al., 2004; Kromer, 2009; Reimer et al., 2013).

The trees at all three subfossil sites are heterogeneous in age, thus we presume the past landscapes were likely closed canopy forests and inter-tree competition growth patterns might obscure a potential climate signal (Cook and Peters, 1981; Pederson et al., 2004). Additionally, our samples are a mix of full cross sections, wedges (both with and without pith), and damaged fragments. Thus, many samples contain growth patterns in the early years not related to a common climate signal or ecological dynamics. In order to remove the samples various geometric growth trends, we standardized the sample's raw ring-width series individually using the program ARSTAN (Cook et al., 2011) with the goal to isolate the common climate signal, retain as much low-frequency variation as possible in the ring widths, but also allow for individual growth anomalies or disturbance. Our default standardization method was either a negative exponential/linear growth curve (NEGEX), as proven optimal by Pearl et al. (2017) for canopy dominant AWC, or a generalized negative exponential Hugershoff curve for sub-canopy samples (Warren et al., 1980; Briffa et al., 2001). For specimens that visibly experienced growth variability due to stand dynamics that was not removed by either a NEGEX or Hugershoff curve we applied a Friedman Super Smoother (Friedman, 1984; Buckley et al., 2010; Pederson et al., 2013). Tree-ring site indices were calculated using difference detrending and the series were transformed using the adaptive power transformation and stabilized based on the interseries correlation (Cook et al., 1995) and a 67% spline (Osborn et al., 1997; Cook and Peters, 1997, 1981). Although a regional curve standardization is often applied to long chronologies to preserve low frequency variability for climate reconstruction, due to sections of low sample depth in the combined record and the many short series in Hundred Acre Cove and Quamquissett, we do not use this approach here (Cook and Peters, 1997; Thomas M Melvin, 2008; Jones, 2009; Briffa and Melvin, 2011).

3. Results

3.1. Site chronologies

3.1.1. Meadowlands, NJ

The trunk diameter mapping of the Meadowlands stumps showed a mixed spatial distribution of various size classes throughout the ancient forest (Zimmermann and Mylecraine,

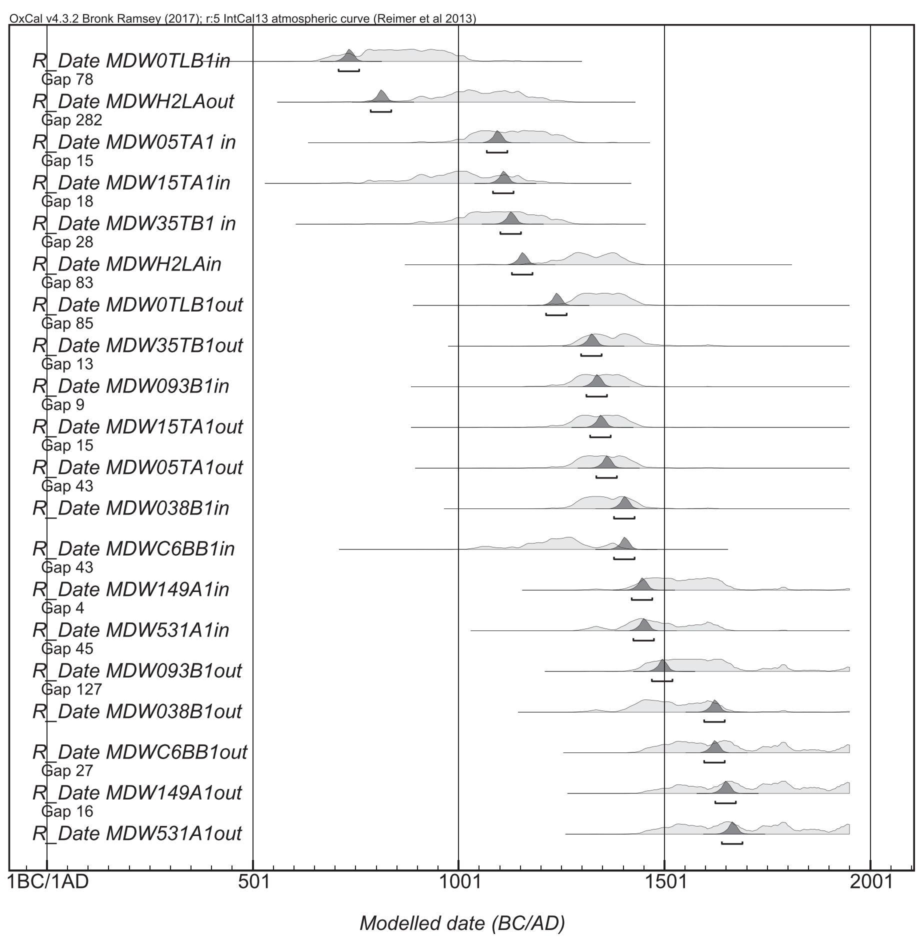

Fig. 3. Conventional modelled radiocarbon dates for the cross-dated Meadowlands samples using OxCal (Ramsey, 2017). Left column contains the sample IDs above the number of cross-dated years between the next consecutively dated sample. The light grey range shows the probability distribution of the sample's calibrated date based only off its radiocarbon age. The dark grey range is the improved ±50 year range modelled by comparing the full series of dates in the chronology against the IntCal13 calibration curve. The youngest cross-dated Meadowlands samples are within radiocarbon error of modern values (light grey range), thus the modelled dates (dark grey range) shown here represent the oldest possible calibrated dates.

2000). The Meadowlands samples analyzed for this study also suggest a mixed-age stand, with the low precision radiocarbon ages spanning a broad range from 1159 to 247 years B.P. (before present; 1950) (Fig. 2). This range is longer than both the mean Meadowlands series age of 227 years and maximum age of 504 years. Within the radiocarbon uncertainty of the Meadowlands dates, there was at least 50 years of overlap between the Meadowlands samples and the Historical chronology. Our cross-dating procedures identified the best match between the two sites as spanning 1644 to 1725 CE. The overlapping individual series have an average Pearson correlation of $r = 0.48$ ($p < 0.01$), and the Meadowlands samples have a mean correlation with the Historical master of $r = 0.52$ ($p < 0.01$). The final Meadowlands chronology is confidently dated from 787 to 1725 CE, with an interseries correlation of 0.505. The Meadowlands chronology has similar autocorrelation properties to modern New Jersey AWC sites (Fig. 4).

3.1.2. Hundred Acre Cove, RI

The samples from Hundred Acre Cove were damaged, poorly preserved, and contained a small number of rings. The radiocarbon ages of the samples spanned from 2560 years BP to 1140 years BP (Fig. 2). Of the 53 collected AWC samples, 36 were retained in the main chronology, with a mean series length of 76 years and a maximum longevity of 145 years. Eight samples dated much older than the main chronology, between 2080 years BP and 2560 years BP, and 4 segments with less than 50 rings each dated from 1240 to 1140 years BP (Fig. 5). The older ohort cross-dated internally with an interseries correlation of 0.44, and dates from 498–67 ± 22 BCE. The low sample size and ring count of the young cohort impeded statistically confident dating (Morgan, 1975; Fritts, 1976; Baillie, 1982).

The geographic distribution of the Hundred Acre Cove age-cohorts were scattered throughout the site. This age heterogeneity could be suggestive of a mixed aged forest, postmortem taphonomic processes such as tidal currents, or both. The collected pine specimens have a wider range of radiocarbon ages than the AWC. There is a cohort of pine that is much older than any collected AWC (5000 + years BP), a cohort that is contemporary (1290–2100 years BP), and a cohort that is younger (590–730 years BP) than the AWC samples (Fig. 2). The oldest pine samples were found furthest from the cove's open water, adjacent to the edge of the estuary. The youngest samples were taken along the periphery of a non-tidal pond interspersed among AWC.

Conventional radiocarbon dating and cross-dating suggested that sample HAC48 spanned the 774/775 CE radiocarbon excursion. Individual tree-ring ^{14}C measurements from sample HAC48 clearly located the 774 CE excursion (Fig. 6). This made it possible to securely fix the floating chronology to an actual calendar date. $\Delta^{14}C$ in the annual rings increased almost 16.5‰ between the year 773–775 CE. HAC48 records similar $\Delta^{14}C$ values to other northern hemisphere tree-ring $\Delta^{14}C$ measurements from 770 to 780 CE (grey open circles Fig. 6). The year 774 CE in HAC48 has a higher $\Delta^{14}C$ value than 773 CE, but less than 775 CE, similar to sites at a similar latitude as Hundred Acre Cove (red circles Fig. 6). Our maximum

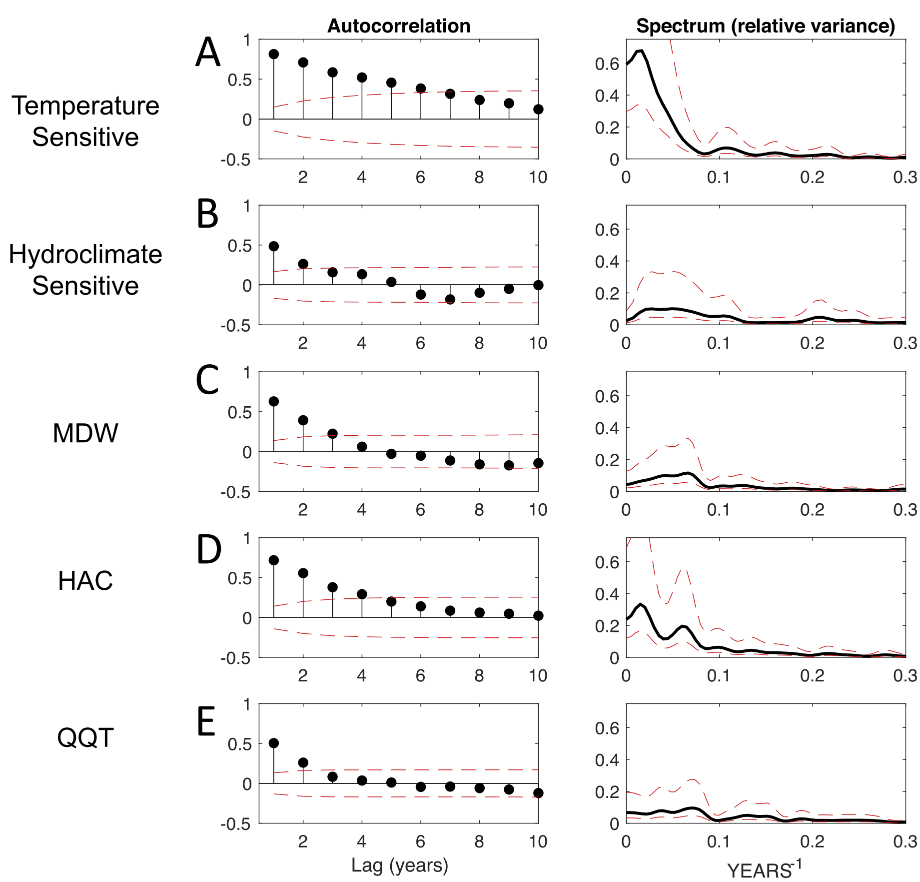

Fig. 4. Autocorrelation functions and spectrum of AWC sites. Left column: the associated autocorrelation of the AWC site (A–E) time series with 10 lagged years. Red dashed lines are the large-lag standard error (Anderson, 1976). Right column: the spectrum of the site chronologies (A–E). Black solid line is the variance of the time series, dashed red lines are the 95% confidence intervals of the spectrum (Jenkin and Watts, 1968). A. Representative living AWC temperature sensitive site. B. Representative living AWC hydroclimate sensitive site. C. Well replicated Meadowlands (MDW) chronology (1200–1410 CE) D. Well replicated Hundred Acre Cove chronology (1617–1817 CE) E. Well replicated Quamquissett (QQT) chronology (1–230 CE). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

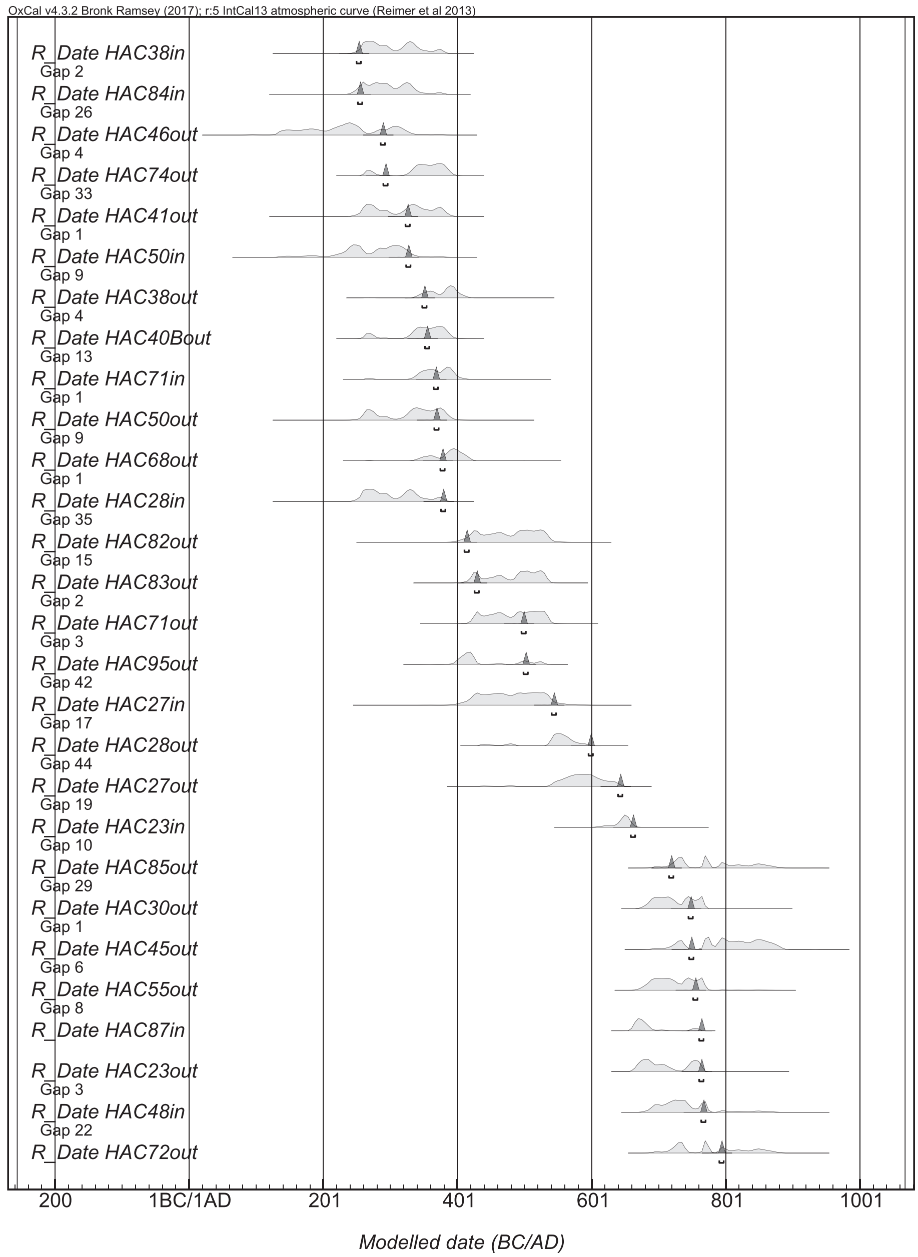

Fig. 5. Conventional modelled radiocarbon dates for the cross-dated Hundred Acre Cove samples using OxCal (Ramsey, 2017). Left column contains the sample IDs above the number of cross-dated years between the next consecutively dated sample. The light grey range shows the probability distribution of the sample's calibrated date based only off its radiocarbon age. The dark grey range is the improved ±10 year range modelled by comparing the full series of dates in the chronology against the IntCal13 calibration curve.

Δ^{14}C measurement is in year 775 CE, while the record from Albania (Seim et al., 2012) has its highest Δ^{14}C value in 776 CE, however the values are within error of each other and within the uncertainty spanned by other sites at a similar latitude. Encouragingly, the discovery of the 774/775 Δ^{14}C jump in HAC48 confirmed that our conventional radiocarbon and ring-width constrained cross-dating approach alone had already dated the main Hundred Acre Cove chronology within 6 years. The absolutely dated Hundred Acre Cove chronology spans 205–817 CE with an interseries correlation of $r = 0.4$.

3.1.3. Quamquissett, MA

Quamquissett contains the oldest AWC samples of all three sites, and has the smallest range of radiocarbon dates (2779-1718 years BP, Fig. 2). The mean series length is 86 years with a maximum length of 174 rings. The oldest dated samples in Quamquissett were found along the periphery of the tidal inlet, although similar to Hundred Acre Cove storm tidal activity likely translocated many of the samples. Two distinct age cohorts exist in Quamquissett, one dating mainly within the Common Era (Fig. 7, bottom), the other dating earlier (Fig. 7, top). Two series bridge these cohorts, and are dated at the highest statistical match within radiocarbon constraints of ±10 years. The final Quamquissett chronology contains 26 samples, dates from 411 BCE to 230 CE, and has an interseries correlation of $r = 0.4$.

3.2. Combined record

Due to the long series length of Meadowlands samples, the low precision radiocarbon dates obtained by the 'speed dating' method

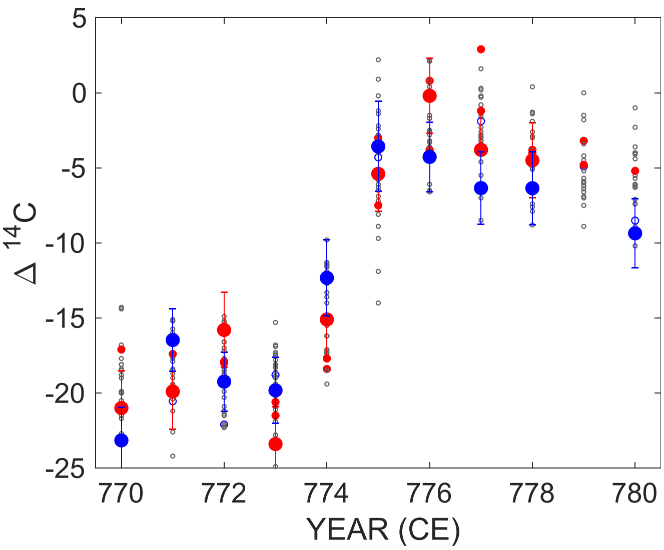

Fig. 6. Annual $\Delta^{14}C$ measurements of HAC48 and other northern hemisphere tree-ring chronologies over the years 770–780 CE. Blue circles and error bars are annual $\Delta^{14}C$ measurements taken from sample HAC48 (41.76°N, this study). Large red circles and error bars are annual $\Delta^{14}C$ measurements from Albania (41.8°N), small red circles are annual $\Delta^{14}C$ measurements from other sites at latitudes 40–44°N. Grey open circles are all other northern hemisphere measurements. Data from Büntgen et al. (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

were sufficient to verify our connection to the historical chronology, extending the New Jersey master chronology back to 787 CE. The absolutely dated Hundred Acre Cove chronology therefore overlaps with the Meadowlands chronology by 30 years from 787 to 817 CE. Although the statistical strength of this overlap is lower than typically suggested for confirmed cross-dating (Morgan, 1975; Fritts, 1976; Baillie, 1982), the exact calendar age of the Hundred Acre Cove chronology due to the identification of the 774 radiocarbon excursion limits all dating uncertainties to the Meadowlands chronology, which is itself tied to the living Historical series. The overlapping Hundred Acre Cove and Meadowlands series have a mean correlation of $r = 0.42$ ($p < 0.05$) as dated, and no better statistical fit was found within the radiocarbon constraints. The Quamquissett chronology was visually and statistically matched with the early Hundred Acre Cove series with a correlation of $r = 0.49$ ($p < 0.01$) over a period of 25 common years (205–230 CE). The number of years in this overlap is also lower than recommended for statistical confirmation of cross dating based on ring widths alone (Morgan, 1975; Fritts, 1976; Baillie, 1982); however, this match is the strongest given the tight radiocarbon constraints of Quamquissett (±10 years) and exact placement in time of Hundred Acre Cove. The resulting combination chronology using Meadowlands, Hundred Acre Cove, and Quamquissett spans the years 411 BCE to 1725 CE, with the largest sample depth for subfossil material spanning the years 714–814 CE and 1190-1403CE (Fig. 8). This chronology is linked to the Southern New Jersey Historical and modern records with significant correlations ($r = 0.52$, $p < 0.01$) over an 81 year overlap, extending our subfossil record to connect with the present.

4. Discussion

4.1. Climatological interpretation

The majority of modern AWC in the Northeast are significantly correlated with temperature in their tree-ring width (Pearl et al., 2017, 2019). The climate sensitivity of living AWC ring-width south of 41°N however is often low for both precipitation and temperature (Hopton and Pederson, 2005; Pearl et al., 2017, 2019); thus, for paleoclimate applications, the AWC stands in the northernmost extent of the species' range are preferred.

As might be predicted based on the above observations, the Meadowlands chronology (located at a lower latitude than 41°N, the approximate threshold for significant climate sensitivity) does not have autocorrelation or spectral properties indicative of a temperature signal (Fig. 4) (Pearl et al., 2019). As with many tree species in the Northeast, temperature signals in the Meadowlands chronology tree-ring width are likely mixed with a confounding drought signal (Cook and Jacoby, 1977; Conkey, 1979; Pederson et al., 2004; Alexander et al., 2019). Hundred Acre Cove, however, is north of 41°N and has large and persistent long-lagged autocorrelation values that suggest that it was a temperature-sensitive AWC swamp (Fig. 4) (Lamarche, 1974; Pearl et al., 2019).

The Quamquissett paleoforest inhabited a kettle hole environment (Bennett and Glasser, 2011). AWC in ombrotrophic kettle hole environments along the coast are dominantly moisture sensitive as they depend on precipitation for their fresh water (Pearl et al., 2019). The modern ombrotrophic kettle hole AWC chronologies have significant but only short-lag autocorrelation and significant high frequency spectral properties (Fig. 4) (Pearl et al., 2019). The Quamquissett chronology, unsurprisingly, has time series characteristics of a hydroclimate sensitive site.

Although climate interpretation of many parts of the record are limited by low sample replication, we explored the tree-ring record for indicators of extreme temperature events in the ring width as indicators of possible climate sensitivity. These indicators usually took the form of unusually narrow ring widths (Fig. 9), which correlate with known marker years in a range of long temperature records for the northern hemisphere (Fig. 9). In this sense the combined chronology could be both verified and developed for further research. For example, the year 1601 CE was used as a marker year in our cross-dating, as it is anomalously small compared to the surrounding decade in the Meadowlands chronology. This could be an indicator of the hemispheric cooling following the eruption of Peru's Huaynaputina volcano in 1600 CE (Briffa et al., 1998; Salzer and Hughes, 2007; Verosub and Lippman, 2008; Anchukaitis et al., 2017). In the Hundred Acre Cove chronology the ring widths from 627 to 629 CE are also extremely suppressed, possibly in response to low temperatures after the 626 CE eruption that is also marked by frost rings in western bristlecone pines (Figs. 8 and 9) (Brunstein, 1995; Salzer and Hughes, 2007; Sigl et al., 2015). In addition, multiple Hundred Acre Cove samples have small rings and exceptionally narrow latewood at years 537, 540, and 542 CE, connected with the now widely established climatic forcings of two other large volcanic eruptions (Fig. 9) (Brunstein, 1995; Salzer and Hughes, 2007; Larsen et al., 2008; Sigl et al., 2015; Toohey et al., 2016; Helama et al., 2019; Dull, 2019).

Unlike long temperature records, which can contain marker events from global scale changes in radiative forcing, hydroclimate variability in coastal New England is more localized (Brown et al., 2010; Kunkel et al., 2013). It is difficult, therefore, to validate our Quamquissett chronology against other pre-instrumental climate records. Nearby records of sea level and hurricanes (Donnelly, 2006; Kemp et al., 2015; Kopp et al., 2016; Donnelly et al., 2015) give indication of extreme events and coastal processes, but are generally too low-resolution or do not extend far enough in time to adequately make annual-scale comparisons. As the Meadowlands, Hundred Acre Cove, and Quamquissett sites are sensitive to different climate parameters, we cannot view our full Common Era chronology (Fig. 9) as reflecting a single climate variable through time, but it is a representation of the potential for AWC records to

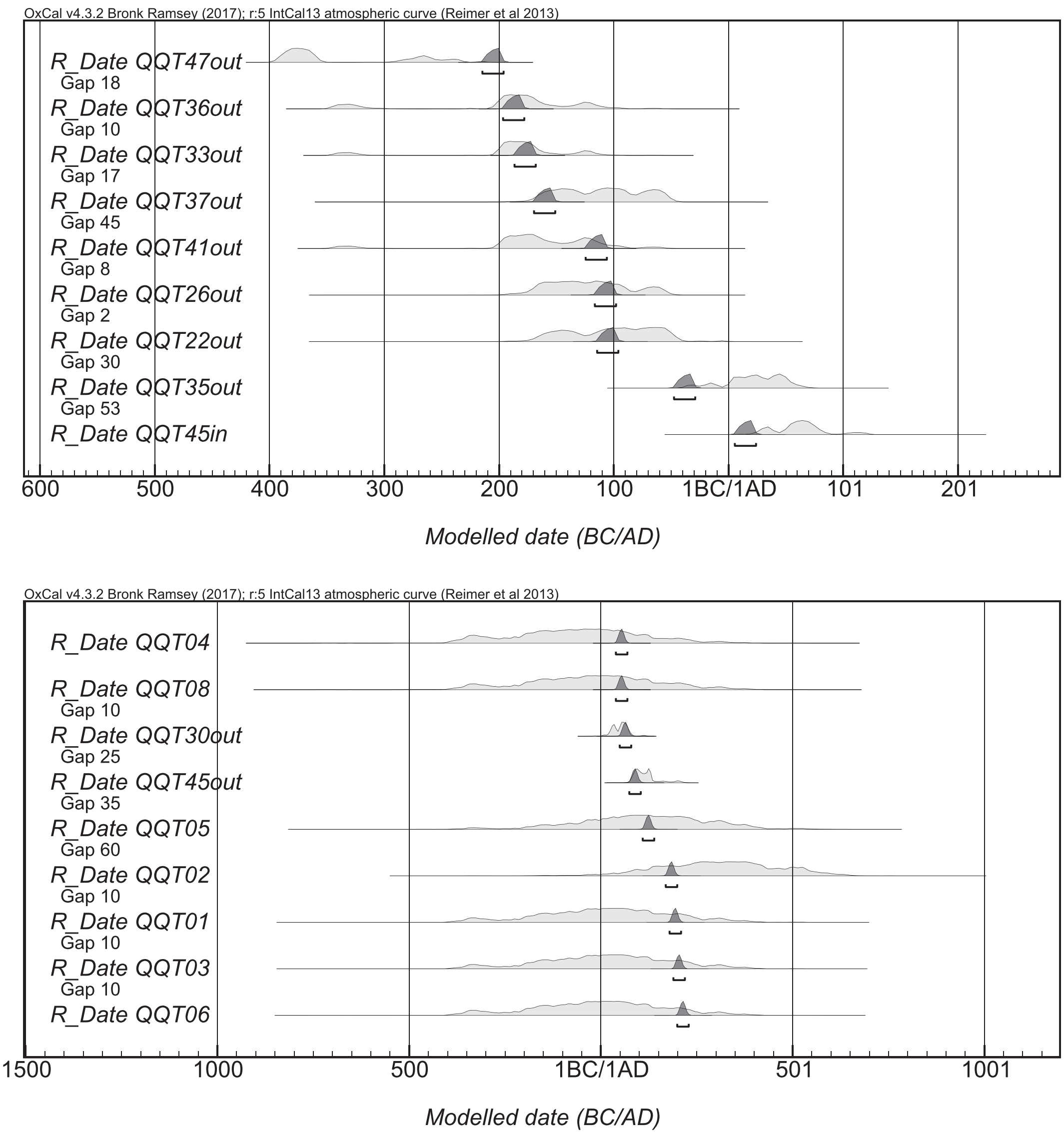

Fig. 7. Conventional modelled radiocarbon dates for the cross-dated Quamquissett samples using OxCal (Ramsey, 2017). Top: the older Quamquissett cohort modelled radiocarbon dates Bottom: the younger Quamquissett cohort. Left column contains the sample IDs above the number of cross-dated years between the next consecutively dated sample. The light grey range shows the probability distribution of the sample's calibrated date based only off its radiocarbon age. The dark grey range is the improved ± 10 year (top) or ± 13 year (bottom) range modelled by comparing the full series of dates in the chronology against the IntCal13 calibration curve.

cross-date across coastal regions of New England.

4.2. Ecological interpretation

The original stem diameter mapping (Zimmermann and Mylecraine, 2000), and the distinct age cohorts identified by radiocarbon measurements (Fig. 2), show that Meadowlands was a mature AWC stand that was heterogeneous in age, likely from selective harvesting by early colonists. Rarely do modern AWC swamps have a similarly diverse age structure, often due to recent, simultaneous regrowth after extensive harvesting, or possibly as part of the species' episodic regeneration patterns (Motzkin et al., 1993; Motzkin, 1990; Mylecraine et al., 2004). The Meadowlands collection contained the longest-lived AWC documented (MDW0TLB, Fig. 3), with over 500 annual rings. This sample is evidence that without harvesting pressures, we would expect modern AWC in protected wetlands to live at least twice their current age. Both Hundred Acre Cove and Quamquissett mean series ages were much shorter, although this could be attributed in part to the loss of exterior rings broken by tidal currents and marine organisms. Modern AWC mortality in the Meadowlands region is not from logging, which now has very limited markets, but rather the introduction of salt water from rising sea water (Zimmermann and Mylecraine, 2000).

The ancient Hundred Acre Cove wetland hosted age-diverse stands of both AWC and pitch pine (*Pinus rigida*). We find evidence of mature pine trees, prior to, during, and after the presence of AWC. The oldest pine in Hundred Acre Cove (c. 6000 year BP) likely inhabited a landscape with different substrate and hydrological conditions. Local pollen studies show that between 8000 and 6000 years BP, *Betula alleghaniensis* Britt. (yellow birch) greatly expanded its range across New England, resulting in the contraction of the regional pine populations to the sandy coastal areas in Northeast (Bryant and Holloway, 1985). We therefore interpret the pine interspersed at Hundred Acre Cove as boundary communities, growing in uplands along the periphery of the wetland AWC stands.

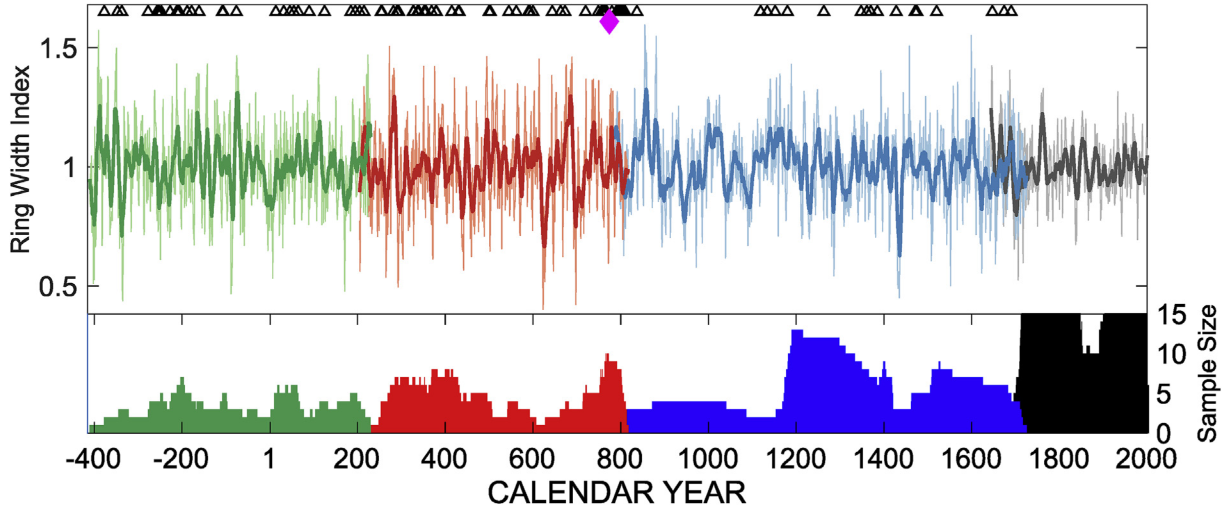

Fig. 8. Multi-millennial northeastern AWC tree-ring record. Individual site autoregressive-standardized chronologies are shown (Cook, 1985). Green record is Quamquissett (QQT), red is Hundred Acre Cover (HAC), blue is Meadowlands (MDW), and black is the Historical (HIS) and modern records. Thicker lines are the 10 year running means for the individual sites. Black triangles indicate location of radiocarbon dates. Pink diamond marks the 774 radiocarbon excursion. Bar graphs below indicate the sample depth (number of trees) of the chronology. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

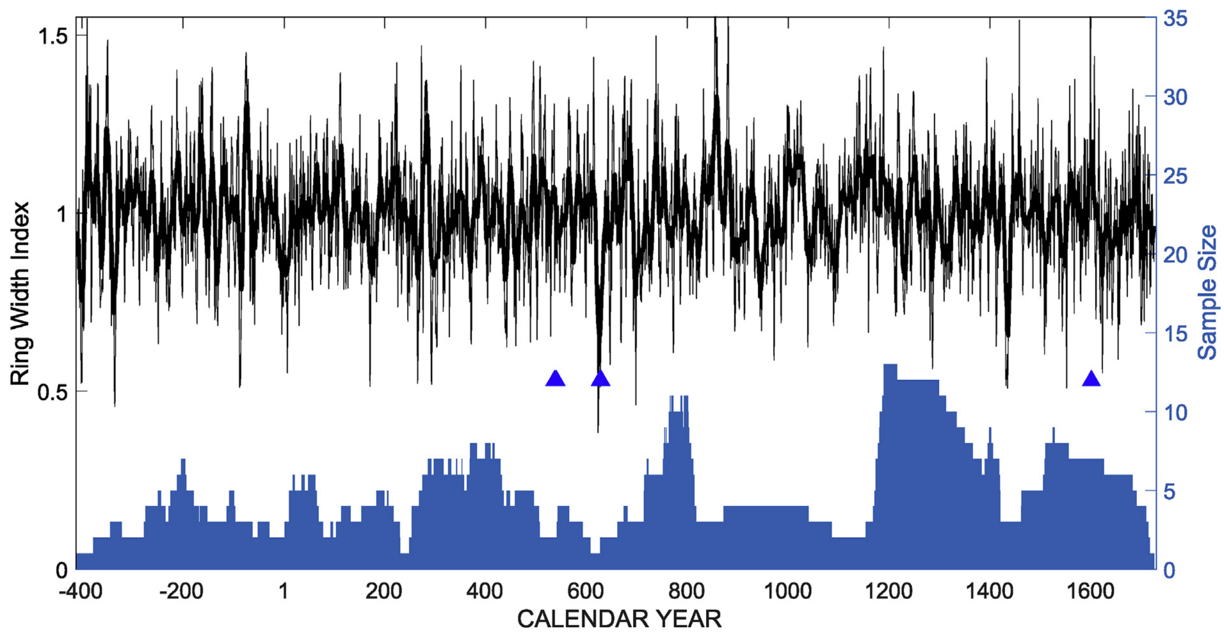

Fig. 9. Full late Holocene subfossil AWC chronology. Black line is the autoregressive-standardized AWC chronology (Cook, 1985), thicker black line is the 10 year moving average. Blue bars represent the sample depth (number of individual trees) of the chronology. Dark blue triangles indicate the marker years discussed in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Although pitch pine can survive in very poor and acidic conditions, its continued presence *in situ* with AWC suggests that Hundred Acre Cove may not have transitioned completely to a saltmarsh environment until the 14th century.

Considering the small size of the Quamquissett site, it is likely that the scattering of age cohorts is representative of mix-aged forest, rather than separate or episodic even-aged stands. The oldest samples in Quamquissett were found along the periphery of the tidal inlet. Modern drowned AWC forests usually have remnant living trees (or the youngest subfossil specimens), along the wetland periphery. The placement of the older Quamquissett samples along the edge of the ancient kettle hole indicate that the death of the paleoforest was likely an abrupt event such as a hurricane in the mid 3rd century. Our results from Meadowlands, Hundred Acre Cove, and Quamquissett show that the even-aged stands of living AWC forests may be a modern feature as a result from intense logging in the region. This could be from simultaneous regrowth after harvesting pressures lessened, or changes in regeneration events such as shifting fire regimes (Motzkin et al., 1993). Protected AWC swamps, therefore, may have a more diverse age structure in the future, with partial stand episodic regeneration (rather than stand replacement) from extreme events, logging, and gap dynamics (Motzkin et al., 1993; Motzkin, 1990; Mylecraine et al., 2004).

4.3. Dating confidence and future work

The individual site chronologies all crossdate internally with interseries correlations of $r = 0.4$ and above, lower although comparable to the interseries correlations of the modern even-aged AWC sites ($r = 0.5$ to 0.7) in the Northeast (Hopton and Pederson, 2005; Pearl et al., 2017). Within each site, distinct age cohorts have stronger interseries correlations of a $r = 0.5$ or better, corroborating their placement in time relative to other similarly aged samples. Our more than 100 radiocarbon measurements here tightly constrain the uncertainty on the dating of floating chronologies to ±10–13 years for Quamquissett, and ± 50 years for Meadowlands (Fig. 2). These tight constraints indicated that the series all had some level of overlap with each other. While the low number of overlapping years between Meadowlands and Hundred Acre Cove, and between Hundred Acre Cove and Quamquissett, remain a source of uncertainty in the regional chronology, the connections we present here are the best fit incorporating both ring-width cross-dating and radiocarbon dating. The match between Meadowlands and Hundred Acre Cove has the lowest statistical agreement over 30 overlapping years ($r = 0.42, p < 0.05$), likely due to the low sample depth and the different climate responses of the two sites. The placement of these two chronologies, however, is based on the strongest agreement of tree-ring patterns within the absolutely dated Hundred Acre Cove chronology constrained by the 774 CE cosmogenic event. No conclusive match was found between the oldest floating Hundred Acre Cove cohort (2080–2560 years BP, Fig. 2) and the Quamquissett chronology, despite overlapping years within radiocarbon error of the early Quamquissett chronology. While relatively weak matches with the best replicated sections of both chronologies are possible within these radiocarbon constraints, the low sample size of the old Hundred Acre Cove cohort limits our confidence in its placement. The cohort of well-preserved pine samples from Hundred Acre Cove offer an opportunity to develop a co-located pine chronology to possibly cross-match the floating Hundred Acre Cove chronology, and deepen our understanding of the paleoecology of the region during the Holocene.

Although all exposed subfossil trees were sampled at Quamquissett and Meadowlands, there remain other, albeit more challenging to collect, AWC samples at Hundred Acre Cove and in other paleoforests submerged in the coastal environment along the New England coast. Many of these sites, however, are still drowned under a meter or more of water at low tide (Gleba, 1978; Emerson, 1981; Englebright and Lamont, 2011). Sampling efforts should be prioritized as many of these paleoforests are quickly disappearing along the coast as sea level rises and ocean currents damage, transport, or bury subfossil pieces. This study's multi-millennial length AWC chronology provides the necessary chronological information for future and continued cross-dating and provenance research of new subfossil and archaeological sites. Recent studies have found additional atmospheric C^{14} excursions and anomalies through annual ^{14}C measurements from tree rings (Ohare, 2017; Miyake et al., 2017). Future work can utilize known circa 9‰ difference in $\Delta\delta^{14}C$ between the years 993 and 994 CE, and the circa 10‰ difference in $\Delta\delta^{14}C$ in the 3–4 years leading up to the year 660 BCE (Ohare, 2017) to further confirm the dating of other AWC samples.

5. Conclusions

This study generated the first multi-millennial late Holocene AWC tree-ring chronology for the northeastern United States. We further demonstrate the utility of combining standard dendrochronological cross-dating procedures and annual ^{14}C measurements to detect atmospheric radiocarbon excursions. These events act as geochronological tie points with which we can place floating chronologies exactly in time. The climate sensitivity of AWC ring-width to regional temperatures (Hopton and Pederson, 2005; Pearl et al., 2017) and in some instances, local hydroclimate (Pearl et al., 2019), make it a valuable, if spatially complex proxy for northeastern coastal climate. Based upon the chronologies' time series characteristics, we interpret the ancient AWC forest at Hundred Acre Cove and Meadowlands to be temperature sensitive sites (Fig. 4). However, at Meadowlands the low latitude of the site location likely effects the strength of the temperature signal of the trees. We interpret Quamquissett to be largely a moisture sensitive site as it is located in an ancient kettle hole (Fig. 4). This potential mixed climate signal limits the use of our regional chronology for continuous straightforward paleoclimate reconstructions at this time. Robust paleoclimate reconstructions will be dependent on further subfossil AWC collection that specifically considers the hydrology and latitude of the samples, and targets wood that can be connected to historical or modern chronologies. Once secured in time, the chronologies can be used for investigations using stable isotopes, wood density, multi-elemental chemistry, and wood anatomy to explore beyond standard ring widths for climate reconstruction. This study presents a novel tree-ring record spanning from 411 BCE to 2016 CE: the longest calendar-dated tree ring chronology in the northeastern United States. With improved sample depth, the Northeast AWC chronology can make an important contribution to the global network of multi-millennial chronologies.

Acknowledgements

This research is funded by the US National Science Foundation Paleo Perspectives on Climate Change program (P2C2; AGS-1304262 and AGS-1501856). The authors of this paper thank Dan Bishop, the Morse family, and the many field assistants who braved the challenging site conditions to collect samples. The authors also thank Aimlee Laderman and Warren Prell for their initial work on Atlantic white cedar in Quamquissett and Hundred Acre Cove. Lamont-Doherty Earth Observatory contribution number 8369.

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