

LETTER • **OPEN ACCESS**

Longevity, climate sensitivity, and conservation status of wetland trees at Black River, North Carolina

To cite this article: D W Stahle *et al* 2019 *Environ. Res. Commun.* 1 041002

View the [article online](#) for updates and enhancements.

Environmental Research Communications



LETTER

Longevity, climate sensitivity, and conservation status of wetland trees at Black River, North Carolina

OPEN ACCESS

RECEIVED

24 October 2018

REVISED

27 February 2019

ACCEPTED FOR PUBLICATION

4 March 2019

PUBLISHED

9 May 2019

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



D W Stahle¹ , J R Edmondson², I M Howard¹, C R Robbins³, R D Griffin⁴, A Carl⁵, C B Hall¹, D K Stahle⁶ and M C A Torbenson¹

¹ Department of Geosciences, University of Arkansas, Fayetteville, AR 72701, United States of America

² The Ancient Bald Cypress Consortium, Fayetteville, AR 72701, United States of America

³ Cape Fear River Watch, Wilmington, NC 28401, United States of America

⁴ Department of Geography, University of Minnesota, Minneapolis, MN 55455, United States of America

⁵ The Nature Conservancy, Wilmington, NC 28401, United States of America

⁶ United States Geological Survey, Bozeman, MT 59715, United States of America

E-mail: dstahle@uark.edu, jesseedmondson@gmail.com, ihowardksu@gmail.com, charlesvrobbins@mac.com, griffin9@umn.edu, acarl@tnc.org, curthall@uark.edu, danny.stahle@gmail.com and mtorbens@uark.edu

Keywords: ancient bald cypress, dendrochronology, radiocarbon dating, climate proxy, wetland conservation

Abstract

Bald cypress trees over 2,000-years old have been discovered in the forested wetlands along Black River using dendrochronology and radiocarbon dating. The oldest bald cypress yet documented is at least 2,624-years old, making *Taxodium distichum* the oldest-known wetland tree species, the oldest living trees in eastern North America, and the fifth oldest known non-clonal tree species on earth. The annual ring-width chronology developed from the ancient Black River bald cypress trees is positively correlated with growing season precipitation totals over the southeastern United States and with atmospheric circulation over the Northern Hemisphere, providing the longest exactly-dated climate proxy yet developed in eastern North America. The Nature Conservancy owns 6,400 ha in their Black River Preserve and the North Carolina legislature is considering establishment of a Black River State Park, but ancient forested wetlands are found along most of this 106 km stream and remain threatened by logging, water pollution, and sea level rise.

Introduction

The forested wetlands of Black River preserve one of the great natural areas of eastern North America (figures 1 and 2; 34.49686°N, 78.24265°W). Many living bald cypress (*Taxodium distichum*) trees at Black River are over 1,000-years old and new research demonstrates that some are over 2,000-years old, making these trees the oldest in eastern North America and as a species the fifth oldest sexually reproducing non-clonal tree taxa on earth. The Black River has been recognized as 'Outstanding Resource Water' by the North Carolina Department of Environment and Natural Resources and is one of the cleanest and high quality waterways in North Carolina (NCDPR 2018). There have been notable attempts to preserve this remarkable stream (Hart 1994), including recognition as a state scenic river, a national scenic river, and a North Carolina State Park. But these proposals for public conservation have yet to succeed and the private Nature Conservancy (TNC) has led preservation efforts in the Black River watershed. TNC now owns 6,400 ha in and adjacent to these old-growth floodplain forests in the Black River Preserve, but thousands of additional hectares with high quality ancient forests remain to be protected. These unprotected ancient forests and the excellent water quality of the Black River are both threatened by logging, water pollution, and development. This article uses dendrochronology and radiocarbon dating to document the extreme longevity of living bald cypress trees at Black River. The discovery of living bald cypress trees well over 2,000-years old provides quantitative evidence for the ecological integrity of this wetland system, extends the proxy paleoclimate record of precipitation variability for the Southeast by over 900 years, and will help advance public and private preservation of the Black River.

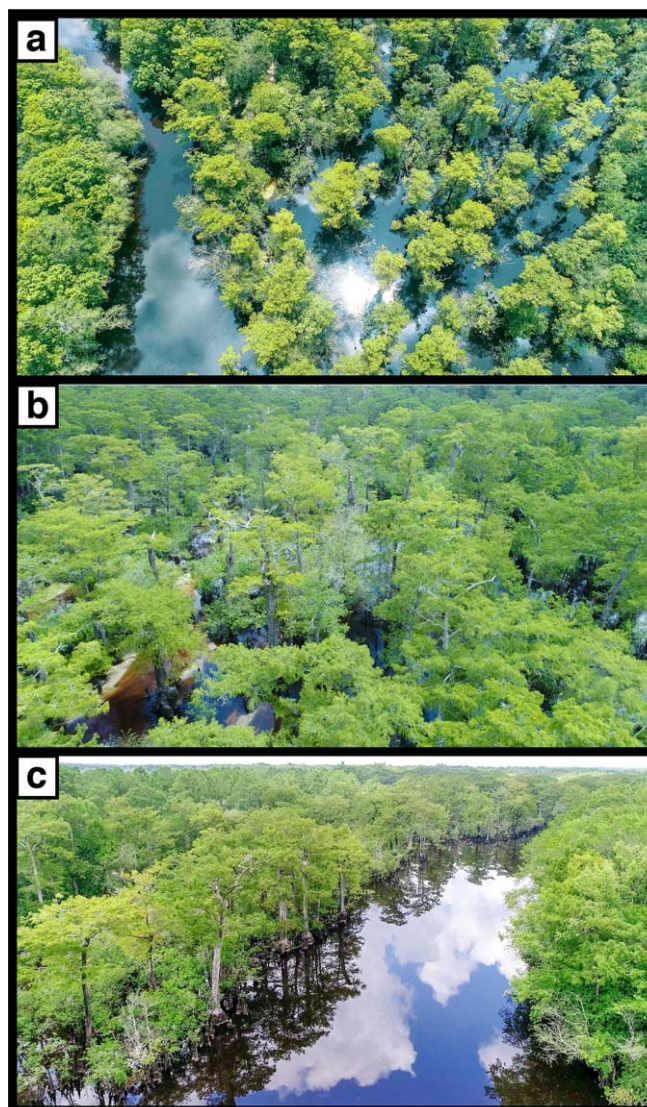


Figure 1. The ancient forested wetlands of Black River preserve the oldest living trees in eastern North America and represent a unique natural heritage deserving of permanent protection [aerial photographs from approximately 80, 60, and 40 m ((a)–(c), respectively)].

Data and methods

Dendrochronology and radiocarbon dating were used to document the age of the living bald cypress trees adjacent to Black River and to develop the proxy tree-ring record of growing season moisture variability for centuries prior to instrumental observations. Non-destructive core samples were all initially collected for paleoclimatic applications (Stahle *et al* 1988, 2012), but subsequent fieldwork focused on using dendrochronology to document the great age of the trees. Simple age determination of the Black River bald cypress is complicated by the frequency of heart rot, but many ancient individuals are not hollow and can be sampled to determine their minimum age with tree-ring and radiocarbon dating. If the true antiquity of bald cypress can be documented then the very presence of exceptionally old living trees could help promote public and private conservation efforts in the Black River watershed.

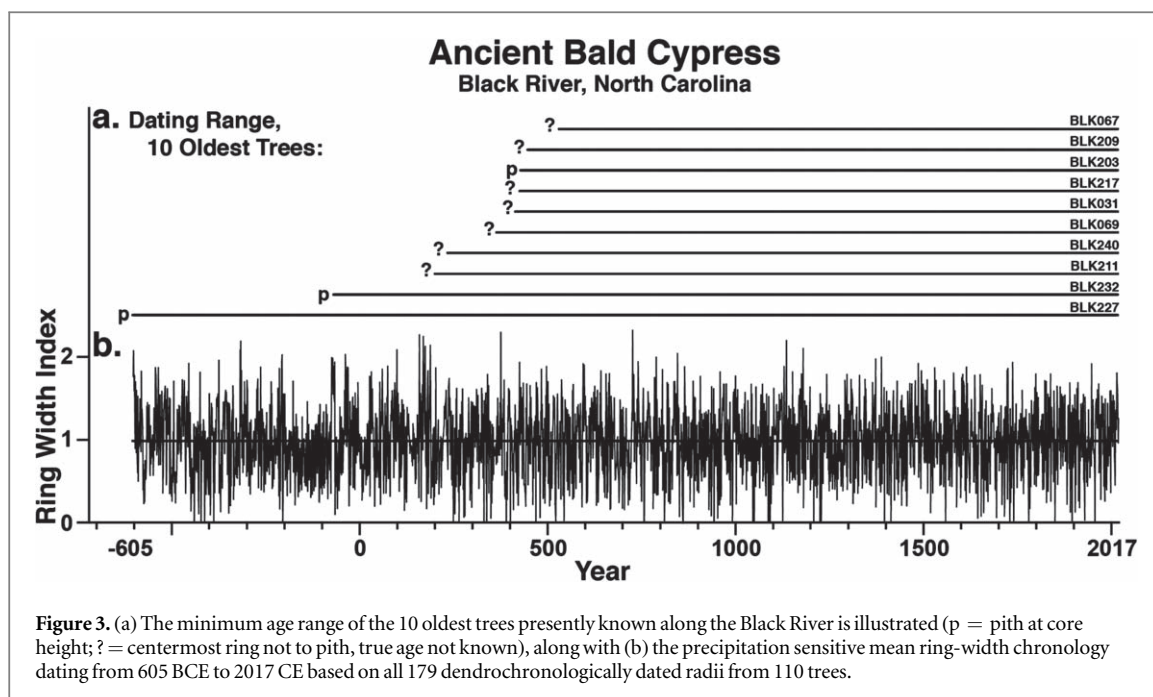
To determine the age of individual old trees and to develop a long and well-replicated tree-ring chronology for climate reconstruction, the core sampling of bald cypress at Black River was selective. To document the oldest trees, solid individuals exhibiting the external characteristics of great age were deliberately sampled. These candidate old trees typically include large twisted and low taper stems with flat-topped crowns, a few heavy limbs, canopy die back, burls, and hollow voids (figure 2). The trees were cored above the basal swell, typically at 3 m, to avoid distortion of the annual rings and to provide a date for the minimum age of the individual. The core specimens were mounted, polished, and all rings were dated to the calendar year of formation under the microscope at 10–70 magnifications using the skeleton plot and visual methods of crossdating (Douglass 1941, Black *et al* 2016). The dated rings were measured with a precision of 0.001 mm and the time series for each core



Figure 2. The deciduous *Taxodium distichum* illustrated here are 1,000 to over 2,000 year old (autumn (a), (c); summer (b)), exhibit the external features of senescent trees, help document the ecological integrity of the Black River system, and provide a high-quality proxy precipitation record for over two millennia.

were submitted to correlation analyses of overlapping segments for quality control of dating and measurement (Holmes 1983). The well-dated ring width time series were then detrended and standardized to remove non-climatic growth trend by fitting a spline function to the measurements from each core (the spline functions had a 50% frequency response equal to 67% of the series length). The raw measurements were first power transformed to reduce bias (Cook and Peters 1997) and the ring-width indices were calculated as the ratio of the measurement value by the value of the fitted spline each year. The mean ring width index chronology for the Black River site was then computed as the biweight robust mean of all individually detrended and standardized core series (Fritts 1976, Hoaglin *et al* 2000, Cook and Krusic 2005).

Correlation analysis was used to document the regional precipitation signal in the mean index chronology from Black River. The chronology was correlated with gridded monthly precipitation totals in the PRISM 4 km resolution monthly precipitation dataset for the eastern United States available from 1895-present (PRISM Group 2004). The highest correlations were noted during the first half of the growing season so the monthly PRISM values were summed to April-June (AMJ) seasonal totals and the Black River chronology was then correlated with these gridded seasonal values to estimate the strength and spatial scale of the moisture signal in these wetland trees. To measure the fidelity of the local to regional precipitation signal in the tree-ring



chronology, the PRISM instrumental AMJ precipitation totals from the grid point closest to the Black River collection site were also correlated with the gridded PRISM AMJ precipitation field for the eastern United States. These correlations all extend from 1895–2010, ending in 2010 when the well replicated portion of the Black River chronology also ends. The tree-ring chronology and the nearest instrumental precipitation grid point data were then correlated with the 500 mb geopotential height field from 1948–2010 using NCEP NCAR Reanalysis (Kalnay *et al* 1998) to document the large-scale atmospheric circulation features important for precipitation and tree growth in southeastern North Carolina.

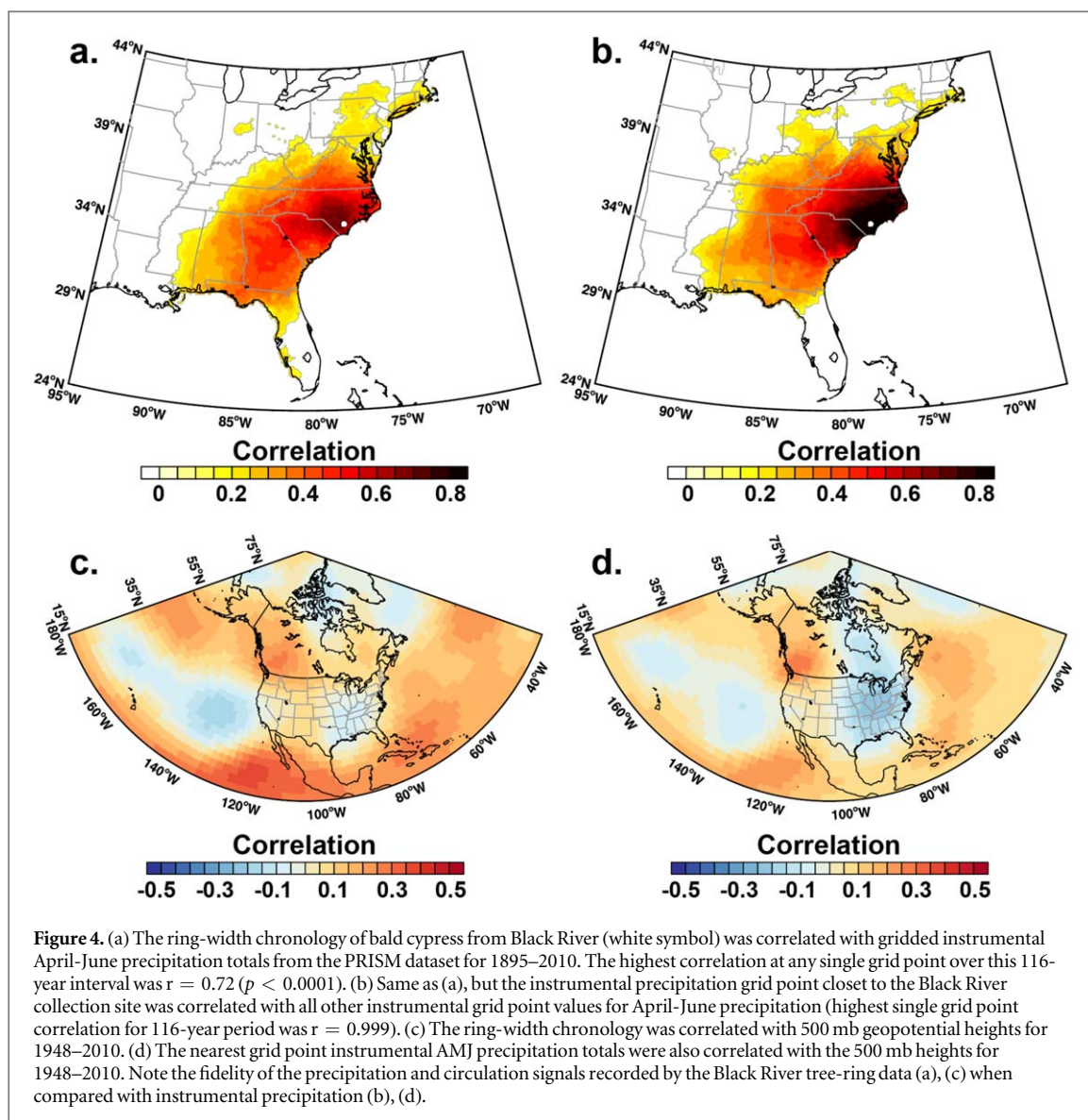
Radiocarbon dating was used to independently test the age of the two oldest individual trees yet located at Black River. Calibrated AMS radiocarbon dates were obtained for cellulose extracted from small core fragments near the center of the two oldest trees [based on the High Probability Density Range Method (Bronk Ramsey 2009) and INTCAL 13 (Reimer *et al* 2013) at Beta Analytic, Inc.]. Because the core fragments are only 5 and 12 mm in diameter, they include multiple annual rings in order to provide sufficient cellulose for radiocarbon analysis. The exact annual tree-ring dating range of each radiocarbon specimen was recorded for precise comparison with the AMS ^{14}C results.

Results

The oldest trees located thus far at Black River are found in a 300 ha section known locally as the Three Sisters Cove, but centuries to millennium old individuals are still present along nearly the entire length of the stream. Dendrochronological analysis of selected tree cores has identified several trees over 1,000-years old and two over 2,000-years old (figure 3(a)). The innermost dated ring on tree BLK232 is 70 BCE and for BLK227 it is 605 BCE, making them at least 2,088- and 2,624-years old in 2018, respectively. Both tree-ring dates represent the minimum age of each tree because they were cored above the basal swell at 3 m above the swamp floor. No specific information is available on the time required for saplings to reach a height of 3 m, but growth rates are very slow at Black River.

The tree-ring dating for both of these very old trees has been independently confirmed with radiocarbon dating, within the dating precision of the AMS ^{14}C estimates. The inner core fragment for BLK227 was tree-ring dated from 548–600 BCE and is within the 95% CI of the AMS ^{14}C result for this tree (i.e., AMS ^{14}C = 788–537 BCE; Laboratory Number Beta-497625). The inner core fragment for BLK232 was tree-ring dated from 34–43 BCE, also within the 95% CI for the AMS ^{14}C result for this ancient tree (i.e., 118 BCE to 26 CE; Laboratory No. Beta-497626).

Heart rot is prevalent in the largest and oldest trees at Black River (e.g., figure 2(a)) but there is evidence suggesting that several other bald cypress trees are over 2,000-years old along this stream. We extracted core samples from four trees with innermost rings that tree-ring dated to at least 200, 235, 395, and 427 CE (figure 3(a)), but these cores did not approach the true center ring due to heart rot or other irregularities. Given the very slow growth rates of these particular trees and all other sampled cypress at Black River, which is only 4.3



cm of radial expansion per century, it is likely that these four trees are also over 2,000-years old [i.e., mean annual ring width = 0.43 mm (std dev = 0.31); $n = 179$ radii from 110 trees). Because we have cored and dated only 110 living bald cypress at this site, a small fraction of the tens of thousands of trees still present in these wetlands, there could be several additional individual bald cypress over 2,000-years old along the approximately 100 km reach of Black River.

The ancient bald cypress trees at Black River record a unique and otherwise unavailable record of annually resolved climate variability and change in the exactly dated annual growth rings. The long tree-ring chronology derived from the ancient bald cypress exhibits dramatic interannual, decadal, and multidecadal variability (figure 3(b)) and is positively correlated with growing season rainfall totals over the southeastern United States (figure 4(a)), in spite of the frequently flooded conditions that prevail in these forested wetlands. This strong positive precipitation response at Black River, which has been detected in all other available bald cypress chronologies (Stahle and Cleaveland 1992, Stahle *et al* 2012), reflects large inter-annual variability in water levels, intense evapotranspiration demand during the growing season, root system stratification near the wetland soil surface by frequent anoxic conditions at depth, and the flux of well-oxygenated water through the root zone (e.g., Davidson *et al* 2006, Stahle *et al* 2012). Dendroclimatic reconstructions of rainfall based on Black River and other bald cypress chronologies from the region have revealed decade-long droughts and pluvials during colonial and pre-colonial times that exceed any measured during the modern period (Stahle *et al* 1988), including the severe droughts that impacted the first English attempts to settle in America at the Roanoke Island and Jamestown colonies (Stahle *et al* 1998).

The regional precipitation signal encoded in the Black River chronology (figure 4(a)) closely follows the region-wide pattern of correlation for the instrumental precipitation data from southeastern North Carolina

(figure 4(b)). The correlations between the chronology and gridded precipitation totals are not as strong as the correlation between the gridded instrumental data at adjacent grid points, of course, but the tree-ring chronology can explain approximately half of the variance in nearby instrumental AMJ precipitation totals and has the virtue of spanning the past two millennia. The Black River tree-ring chronology is also correlated with the 500 mb geopotential height field over the Northern Hemisphere during the spring-early summer (figure 4(c)). The spatial pattern of correlation is similar for the co-located PRISM instrumental AMJ precipitation totals and the correlation maps (figures 4(c), (d)) indicate that tree growth and AMJ precipitation both tend to be reduced during the positive phase of the Pacific/North American (PNA) pattern of mid-tropospheric circulation as has been previously described for the eastern United States (Leathers *et al* 1991). The geopotential height correlations are higher in the Pacific and Atlantic sectors for the tree-ring chronology, but they are higher for the instrumental precipitation totals over the eastern United States (figures 4(c), (d)). These differences may arise from the fact that bald cypress growth is also negatively correlated with temperature (Stahle *et al* 1988), which is also well correlated with the PNA during the winter-spring.

Discussion and conclusions

Living trees over 2,000-years old are extremely rare worldwide. Only eight species have been proven with dendrochronology to live for more than 2,000 years (Brown 1996). Six of these species are located in the western United States, one in Chile, and now bald cypress at Black River, North Carolina. The oldest known Black River bald cypress (BLK227) has an inner ring date of 605 BCE, based on crossdating with other trees at Black River back to as early as 70 BCE, but with four radii from just this one old tree from 70 to 605 BCE. This means that BLK227 is at least 2,624-years old in 2018, moving bald cypress to number five on the worldwide list of the oldest-known continuously living, sexually reproducing, non-clonal tree species based on dendrochronology. Bald cypress is the oldest-known wetland tree species on earth. Only individual trees of Sierra juniper (*Juniperus occidentalis*) at 2,675-years, giant sequoia (*Sequoiadendron giganteum*) at 3,266, alerce (*Fitzroya cupressoides*) at 3,622, and Great Basin bristlecone pine (*Pinus longaeva*) at 5,066-years old are known to live longer than Black River bald cypress. The actual difference in the age of the oldest-known bald cypress and Sierra juniper is likely very low because of the extremely slow growth rates at Black River and the time required for trees to reach the 3 m sampling height.

The maximum longevity of wetland tree species has not been well documented. The oldest-known are the millennia-old bald cypress at Black River, but Montezuma bald cypress (*T. mucronatum*) in the 1,200 to 1,500-year age class have been reported in Mexico (Villanueva-Diaz *et al* 2007) and *Pilgerodendron uviferum* at least 859-years old have been noted in southern Chile (Aravena 2007; *P. uviferum* is found in both upland and bog sites in Valdivian temperate rainforests). The oldest-reported angiosperm species from a wetland settling appears to be a *Nyssa silvatica* at 679-year old from a bog in New England (Di Filippo *et al* 2015), and a *Nyssa aquatica* at least 600-years in the forested wetlands of Bayou DeView, Arkansas (Stahle, unpublished data). *Macaranga acaciifolia* over 500-years old have been reported from the seasonally flooded forests of the central Amazon based on tree-ring analysis (Schöngart *et al* 2005).

Certain nutrient-poor wetlands may be consistent with a model of 'longevity under adversity' which Schulman (1954) applied to conifers in semi-arid America, including bristlecone pine (*Pinus longaeva*), the oldest known living trees on earth (Schulman 1958). The adverse low pH, limited nutrients, and frequently flooded conditions at Black River not only exclude most bottomland hardwood tree species, they are also associated with extremely slow growth rates of bald cypress on this black water stream. The differences on tree growth rates between the seasonally flooded forests of the várzea and igapó in the central Amazon have also been attributed to nutrient availability in these white-water and black-water forested wetlands, respectively (Schöngart *et al* 2005).

The long tree-ring chronology developed from these ancient bald cypress trees has considerable paleoclimate value. The strong regional scale moisture signal in this chronology has contributed to the success of tree-ring reconstructions of the Palmer drought severity index (PDSI) on a gridded basis for North America (Cook *et al* 1999, 2007). These PDSI reconstructions in the so-called North American Drought Atlas (NADA) have leveraged the analysis of past droughts and pluvials (Fye *et al* 2003, Cook *et al* 2016), the large-scale climate dynamics responsible for moisture variability over the continent (Coats *et al* 2016, Baek *et al* 2017), and interactions between climate, ecosystem function (Swetnam *et al* 2009, Marlon *et al* 2017), and social impacts over the past two millennia (Stahle and Dean 2011, Burns *et al* 2014). The recently discovered old trees have extended the existing Black River chronology by 970-years (i.e., from 365 CE to 605 BCE), but the chronology is based on only one tree before 70 BCE. Tree-ring samples are available from only 110 trees out of the tens of thousands still present along this stream and it is likely that the chronology can be improved and perhaps extended with additional sampling of old trees. Old relic logs are sparingly present in shallow submerged context

and likely in the thalweg of the main channel on the lower reaches of the Black River. These sources of relic or sub-fossil logs have not been investigated but may help improve and extend the Black River chronology deeper into the Holocene.

The ancient bald cypress forests of Black River survive in the heavily developed agricultural and industrial forest landscape of southeastern North Carolina. Few if any old growth upland hardwood or pine forests of any size are known to still exist in the vicinity of Black River. Exploitation of timber and naval stores began during the colonial era and the Black River was accessible by steamboat from the Cape Fear River during the 19th century (Hart 1994). Many bald cypress and bottomland hardwoods were cut along the Black River, of course, but the old-growth trees that dominate many stands were simply not suited for saw log production (Stahle *et al* 2012). As a result, extensive tracts of uncut ancient forest remain intact along the Black River.

The survival of ancient bald cypress and other tree species at Black River provides qualitative and quantitative evidence for the ecological integrity of this wetland ecosystem. Qualitatively, an excursion on the Black River where clear tea-colored water flows over white sand and among columnar trees of great age is a unique experience and certainly qualifies this stream as one of the great natural areas of eastern North America (figures 1 and 2). Quantitatively, the minimum age determinations of selected old-growth bald cypress trees are based on dendrochronology (figure 3(a)), the most accurate and precise dating method in geochronology. The habitat value of the Black River is further documented by the high surface water quality (a designated Outstanding Resource Water, NCDPR 2018), the presence of rare and endangered species (NCDPR 2018), and the recent observations of threatened wood storks (*Mycteria americana*) and swallowtail kites (*Elanoides forficatus*) in these forested wetlands.

The Nature Conservancy has led the preservation of the Black River, but the state of North Carolina and a few other private landowners have made important conservation contributions as well. A feasibility study to consider the establishment of a state park on the Black River was enacted by the North Carolina General Assembly in 2017 (HB353 in NCDPR 2018) and the Nature Conservancy continues to seek funding to expand their Black River Preserve. Unfortunately, the ancient forests and water quality of the Black River are both imperiled by continued logging, biomass harvesting for wood pellets and garden mulch, and water pollution from confined animal feeding operations and municipal discharge in the watershed. In the longer term, the Three Sisters Cove is only 2 m above mean sea level and is at risk from sea level rise which could occur during the life span of these exceptionally old trees with unmitigated anthropogenic global warming. To counter these threats, the discovery of the oldest known living trees in eastern North America, which are in fact some of the oldest living trees on earth, provides powerful incentive for private, state, and federal conservation of this remarkable waterway.

Acknowledgments

Funded in part by the National Science Foundation (AGS-1266014), The Nature Conservancy, and private donations to the Ancient Bald Cypress Consortium. We thank John and Maggie DeCuevas, Kemp Burdette, Jordan Burns, Graham Hawks, Hervey McIver, Julie Moore, Zack West, and Katherine P Wolff. We appreciate the helpful editorial suggestions of Neil Pederson and an anonymous reviewer. The tree-ring data described in this article are available from the corresponding author (dstahle@uark.edu) and from the International Tree-Ring Data Bank, NOAA Paleoclimatology Program (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>).

ORCID iDs

D W Stahle  <https://orcid.org/0000-0002-8943-2541>

References

- Aravena J C 2007 Reconstructing climate variability using tree rings and glacier fluctuations in the southern Chilean Andes *PhD Dissertation* University of Western Ontario(London) p. 220
- Baek S H, Smerdon J E, Coats S, Williams A P, Cook B I, Cook E R and Seager R 2017 Precipitation, temperature, and teleconnection signals across the combined North American, Monsoon Asia, and Old World Drought Atlases *J. Clim.* **30** 7141–55
- Black B A *et al* 2016 The value of crossdating to retain high-frequency variability, climate signals, and extreme events in environmental proxies *Global Change Biology* **22** 2582–95
- Bronk Ramsey C 2009 Bayesian analysis of radiocarbon dates *Radiocarbon* **51** 337–60
- Brown P M 1996 OLDLIST: a database of maximum tree ages ed J S Dean *et al Tree Rings, Environment, and Humanity: Proc. of the Int. Conf., Arizona* (Tucson) (17–21 May, 1994 *Radiocarbon* vol 1996, pp 727–31 See also <http://rmtrr.org/oldlist.htm>
- Burns J N, Acuna-Soto R and Stahle D W 2014 Drought and epidemic typhus, central Mexico, 1655–1918 *Emerging Infectious Diseases* **20** 442–7

- Coats S, Smerdon J E, Cook B I, Seager R, Cook E R and Anchukaitis K J 2016 Internal ocean-atmosphere variability drives megadroughts in western North America *Geophys. Res. Lett.* **43** 9886–94
- Cook B I, Cook E R, Smerdon J E, Seager R, Williams A P, Coats S, Stahle D W and Villanueva Diaz J 2016 North American megadroughts in the Common Era: reconstructions and simulations *WIRE Climate Change* **145**
- Cook E R and Peters K 1997 Calculating unbiased tree-ring indices for the study of climatic and environmental change *The Holocene* **7** 359–68
- Cook E R and Krusic P J 2005 *Program ARSTAN: A Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modeling, with Interactive Graphics*. Manuscript on file (Palisades, NY: Tree-Ring Lab, Lamont Doherty Earth Observatory of Columbia University) (unpublished manuscript)
- Davidson G R *et al* 2006 Root zone hydrology: why bald cypress in flooded wetlands grow more when it rains *Tree-Ring Research* **62** 3–12
- Douglass A E 1941 Crossdating in dendrochronology *Journal of Forestry* **39** 825–31
- Di Filippo A, Pederson N, Baliva M, Brunetti M, Dinella A, Kitamura K, Knapp H D, Schirone B and Piovesan G 2015 The longevity of broadleaf deciduous trees in Northern Hemisphere temperate forests: insights from tree-ring series *Frontiers in Ecology and Evolution* **3** 1–15
- Fritts H C 1976 *Tree Rings and Climate*. (London: Academic)
- Fye F K, Stahle D W and Cook E R 2003 Paleoclimatic analogs to 20th century moisture regimes across the USA *Bull. Am. Meteorol. Soc.* **84** 901–9
- Hart K 1994 The legend of Black Beauty. *Coastwatch* March/April 1994:10-15 (ISSN 1068-784X)
- Hoaglin D C, Mosteller F and Tukey J W 2000 *Understanding Robust and Exploratory Data Analysis*. (New York: Wiley) p 472
- Holmes R L 1983 Computer-assisted quality control in tree-ring dating and measurement *Tree-Ring Bulletin* **44** 69–78
- Kalnay E *et al* 1998 The NCEP/NCAR 40-year reanalysis project *Bull. Am. Meteorol. Soc.* **77** 437–71
- Leathers D J, Yarnal B and Palecki M A 1991 The Pacific/North American teleconnection pattern and United States climate: I. Regional temperature and precipitation associations *J. Clim.* **4** 517–28
- Marlon J R *et al* 2017 Climatic history of the northeastern United States during the past 3000 years *Climate of the Past* **13** 1355–79
- NCDPR (North Carolina Division of Parks and Recreation) 2018 *Feasibility Study of Establishing a State Park Along the Black River in Sampson* (Raleigh, NC: Bladen, and Pender Counties) p 20 (unpublished manuscript)
- PRISM Climate Group 2004 Oregon State University <http://prism.oregonstate.edu> created 4 2004
- Reimer P J *et al* 2013 INTCAL 13 and MARINE13 radiocarbon age calibration curves 0-50,000 years cal BP *Radiocarbon* **55** 1869–87
- Schöngart J, Piedade M T F, Wittmann F, Junk W J and Worbes M 2005 Wood growth patterns of *Macaranga acaciifolium* (Benth.) Benth. (Fabaceae) in Amazonian black-water and white-water floodplain forests *Oecologia* (<https://doi.org/10.1007/s00442-005-0147-8>)
- Schulman E 1954 Longevity under adversity *Science* **119** 396–9
- Schulman E 1958 Bristlecone pine, oldest known living thing *National Geographic Magazine* **1958** 355–72
- Stahle D W, Cleaveland M K and Hehr J G 1988 North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985 *Science* **240** 1517–9
- Stahle D W and Cleaveland M K 1992 Reconstruction and analysis of spring rainfall over the Southeastern US for the past 1000 years *Bull. Am. Meteorol. Soc.* **73** 1947–61
- Stahle D W and Dean J S 2011 North American tree rings, climatic extremes, and social disasters. ed M K Hughes *et al Dendroclimatology: Progress and Prospects, Developments in Paleoenvironmental Research* Vol 11 Pages 297–327 (Berlin: Springer)
- Stahle D W *et al* 1998 The Lost Colony and Jamestown Droughts *Science* **280** 564–7
- Stahle D W *et al* 2012 Tree-ring analysis of ancient baldcypress trees and subfossil wood *Quat. Sci. Rev.* **34** 1–15
- Swetnam T S, Baisan C H, Caprio A C, Brown P M, Touchan R, Anderson S R and Hallett D J 2009 Multi-millennial fire history of the Giant Forest, Sequoia National Park, California, USA *Fire Ecology* **5** 120–50
- Villanueva-Diaz J, Stahle D W, Luckman B H, Cerano-Paredes J, Therrell M D, Moran-Martinez R and Cleaveland M K 2007 Potencial dendroclimático de *Taxodium mucronatum* Ten. y acciones para su conservación en México *Ciencia Forestal en México* **32** 9–38
- Cook E R, Meko D M, Stahle D W and Cleaveland M K 1999 Drought reconstructions for the continental United States *Journal of Climate* **12** 1145–62
- Cook E R, Seager R, Cane M A and Stahle D W 2007 American Drought: reconstructions, Causes and consequences *Earth Science Review* **81** 93–134