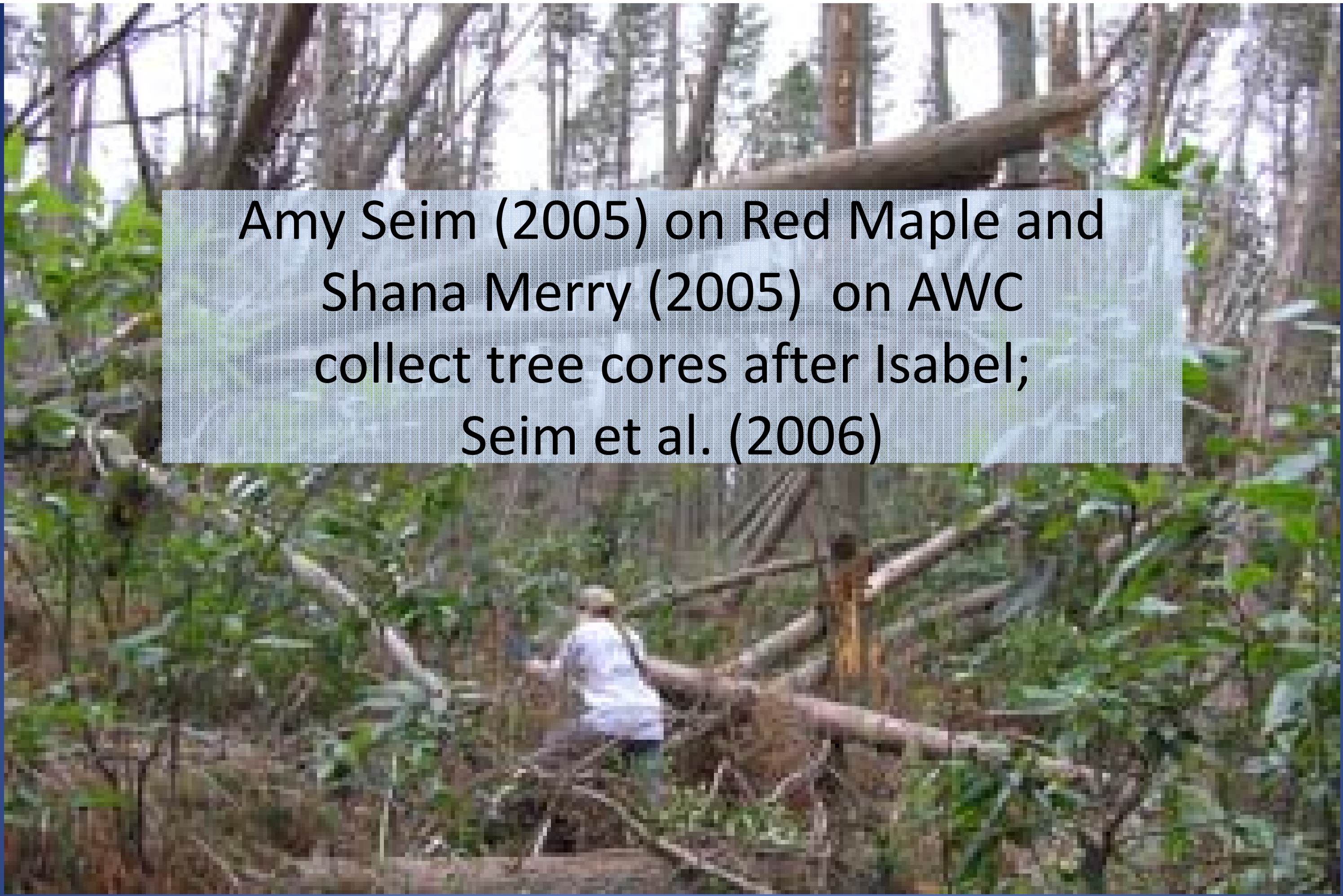
Radial Growth of AWC in Great Dismal Swamp National Wildlife Refuge and its Association with Lake Drummond Water Levels

by Craig Lee Patterson

presented by
Rob Atkinson



Loblolly pine in GDSNWR — Phipps et al. (1979)
AWC in Rhode Island — Golet and Lowry (1987)
AWC in the Northeast — Pederson et al. (2004) and Hopton and Pederson (2005)

Lamont Doherty Earth Observatory at Columbia University

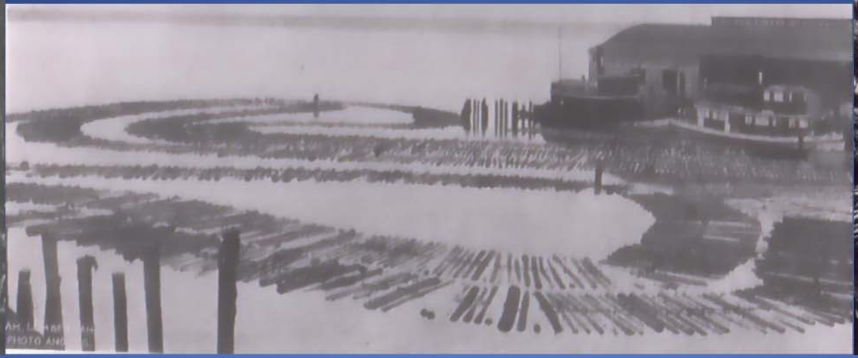
Center for Wetland Conservation
at Christopher Newport University

Presentation outline

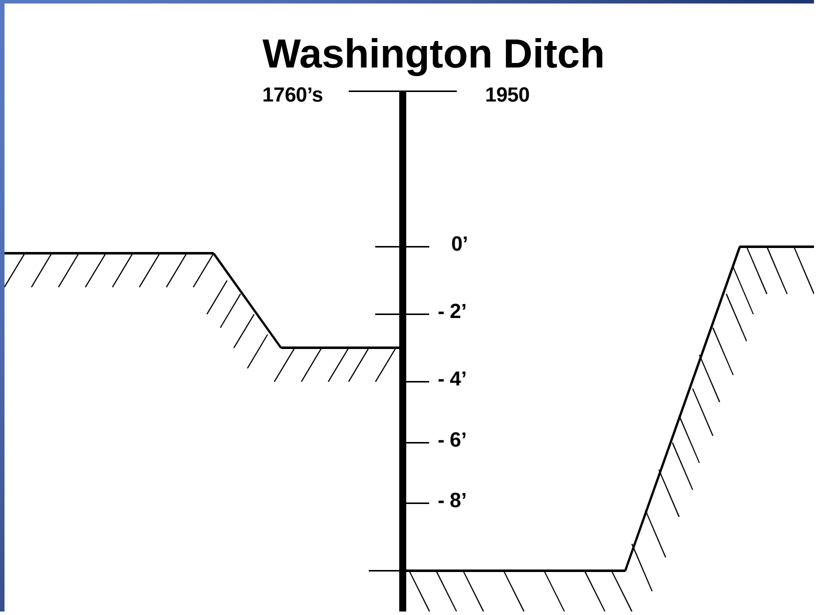
- History
- Methods
- Results/Discussion
- Application: can tree rings predict ecosystem services?

History

Cedar in History

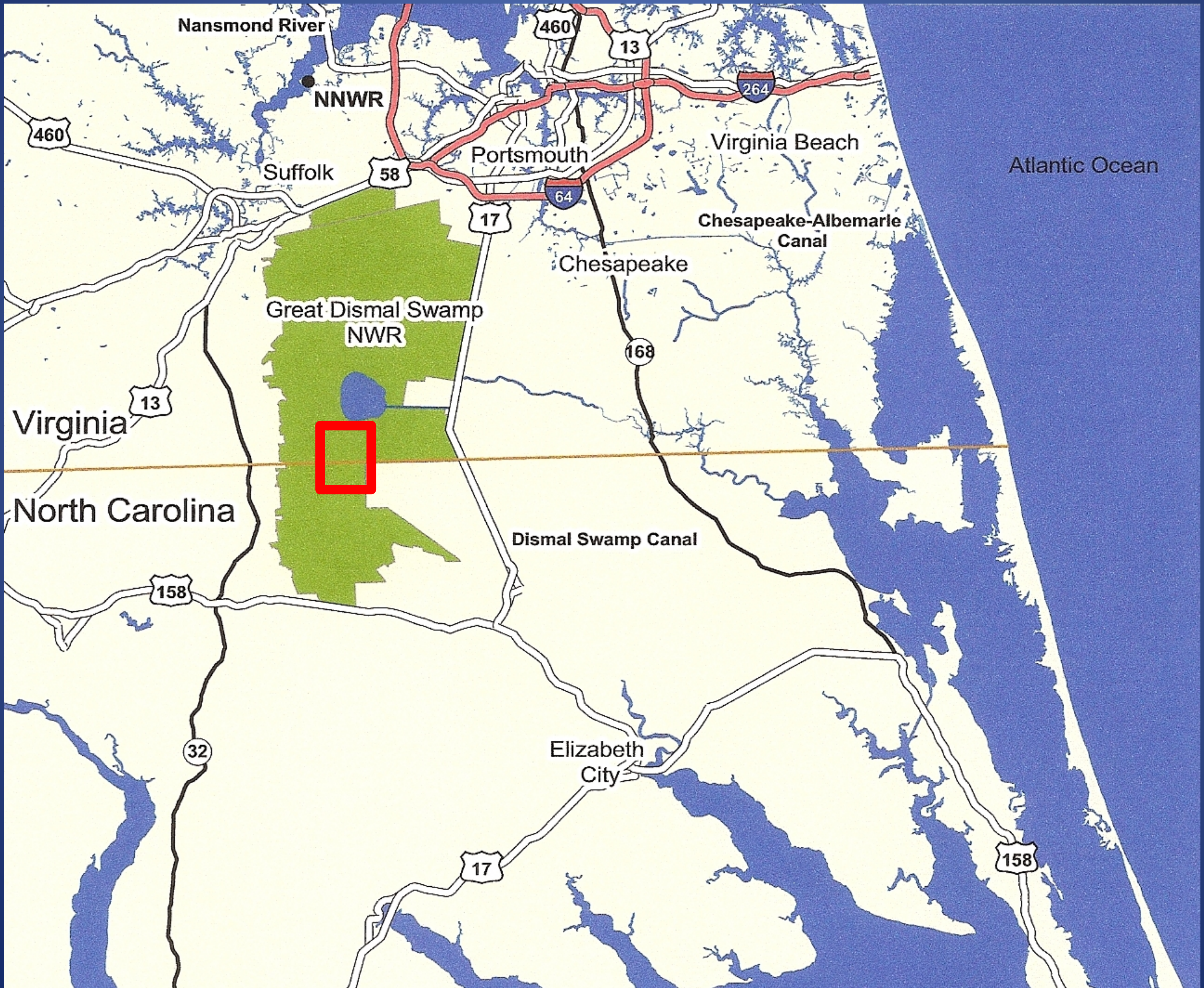


- Cedar is endangered in the northeast (Kalm, 1748).
- Washington Ditch is dug and cedar becomes a major export crop from Great Dismal Swamp (1760s)
- Dismal Swamp Canal is dug and facilitates drainage of GDS (1805)



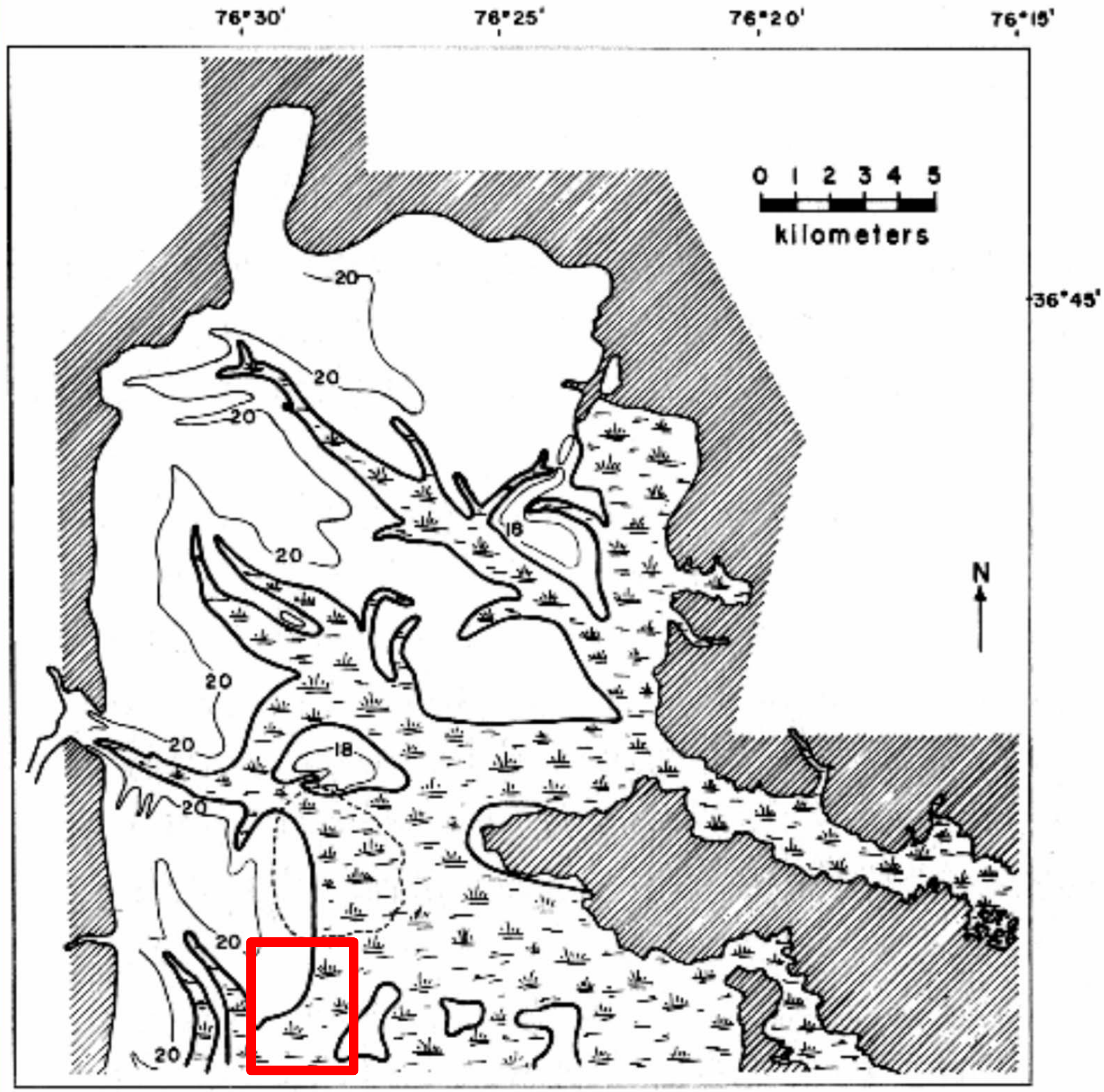
Solution: pair technology and ecological understanding

Historical overview of AWC in GDS



Circa

6000 B.P.



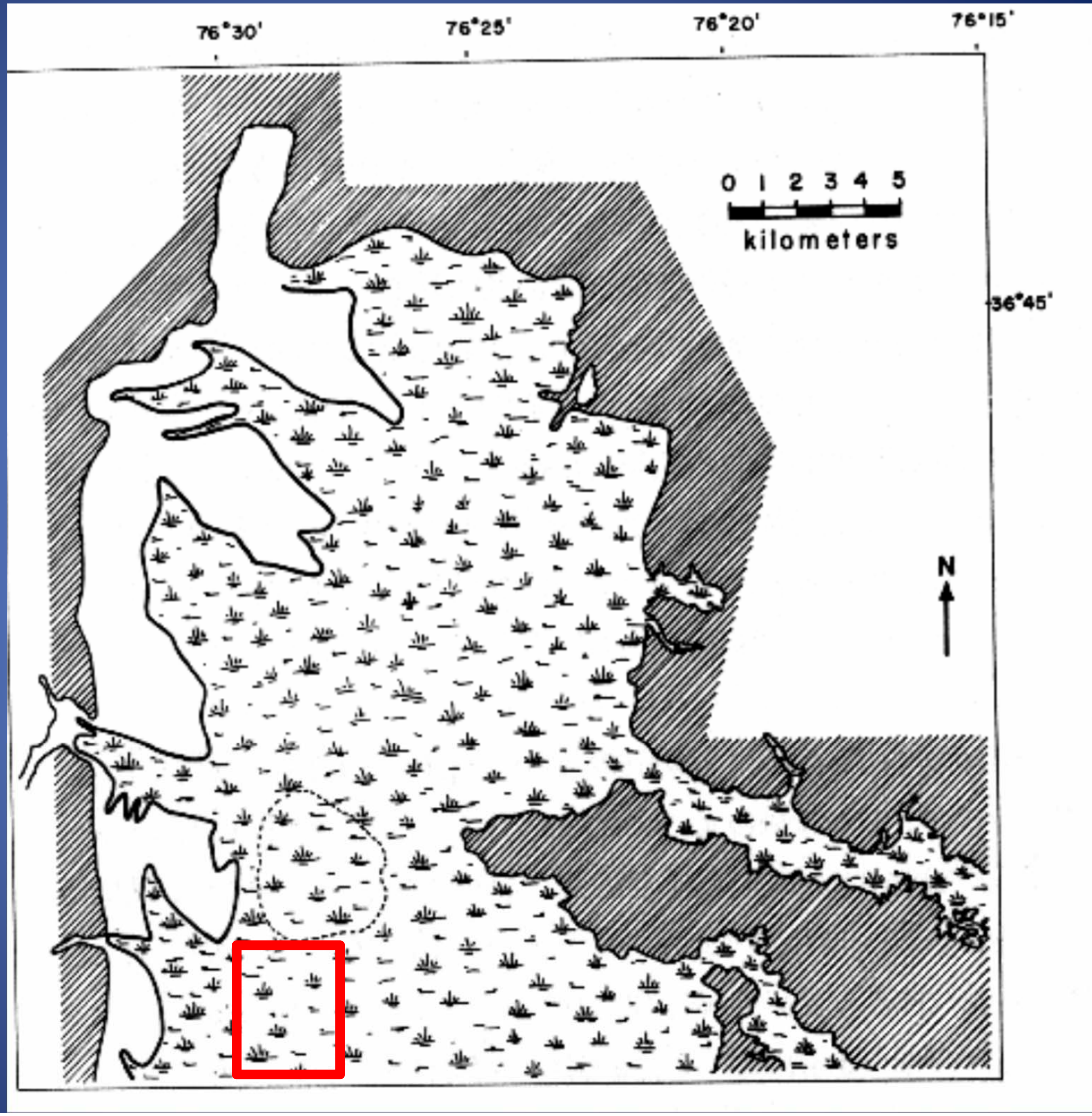
Circa

3500 B.P.

>2 feet 1000 years?

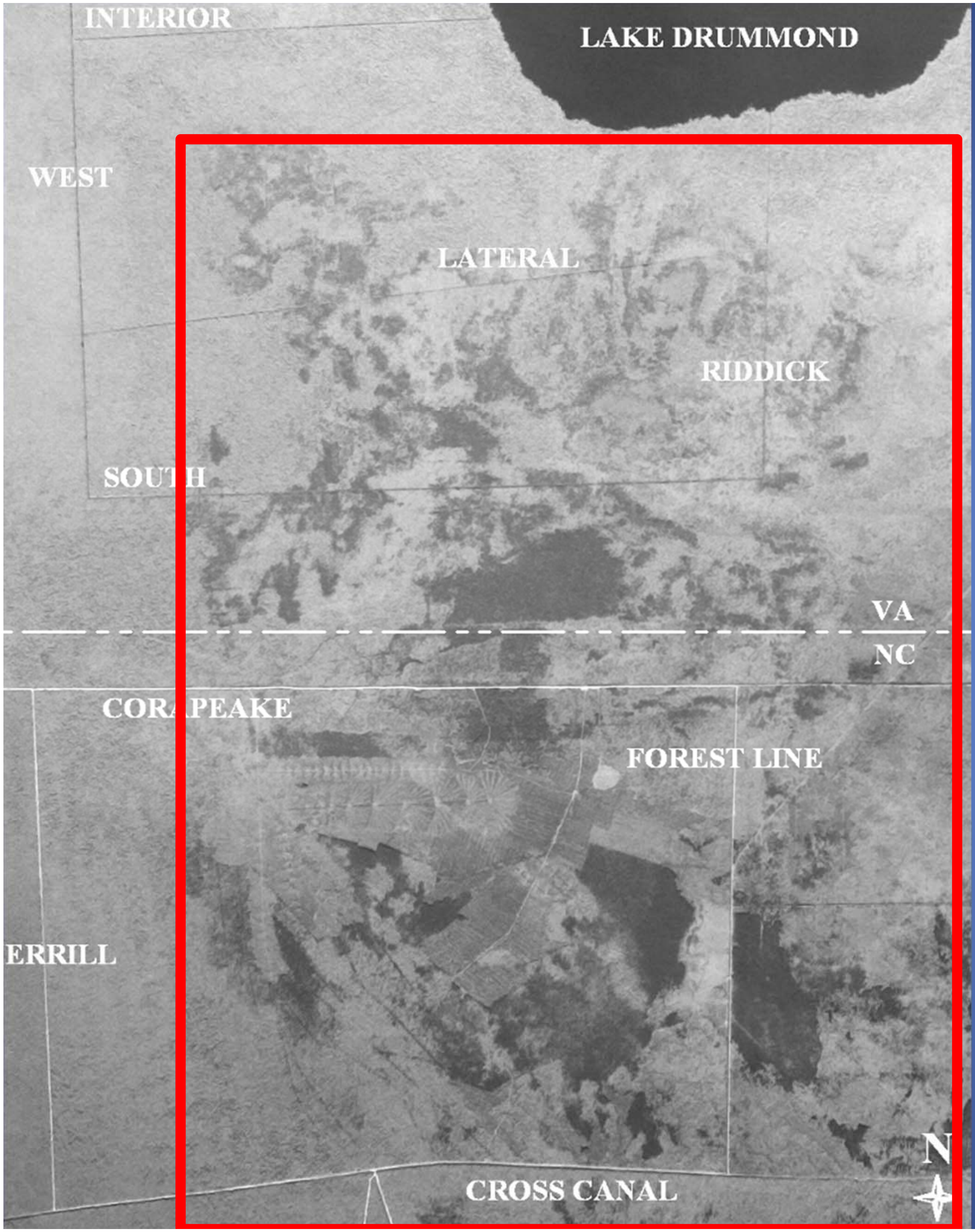
If we lost 4 feet, maybe 2,000 years worth.

~100,000 acres with deep peat deposits, so its back to work!



Early image of Atlantic White Cedar in Great Dismal Swamp

"Showing the fine Juniper (White Cedar) Timber on the holdings of John L. Roper Lumber Company in the Great Dismal Swamp of Virginia and North Carolina. ***About 60,000 acres in this body****."*

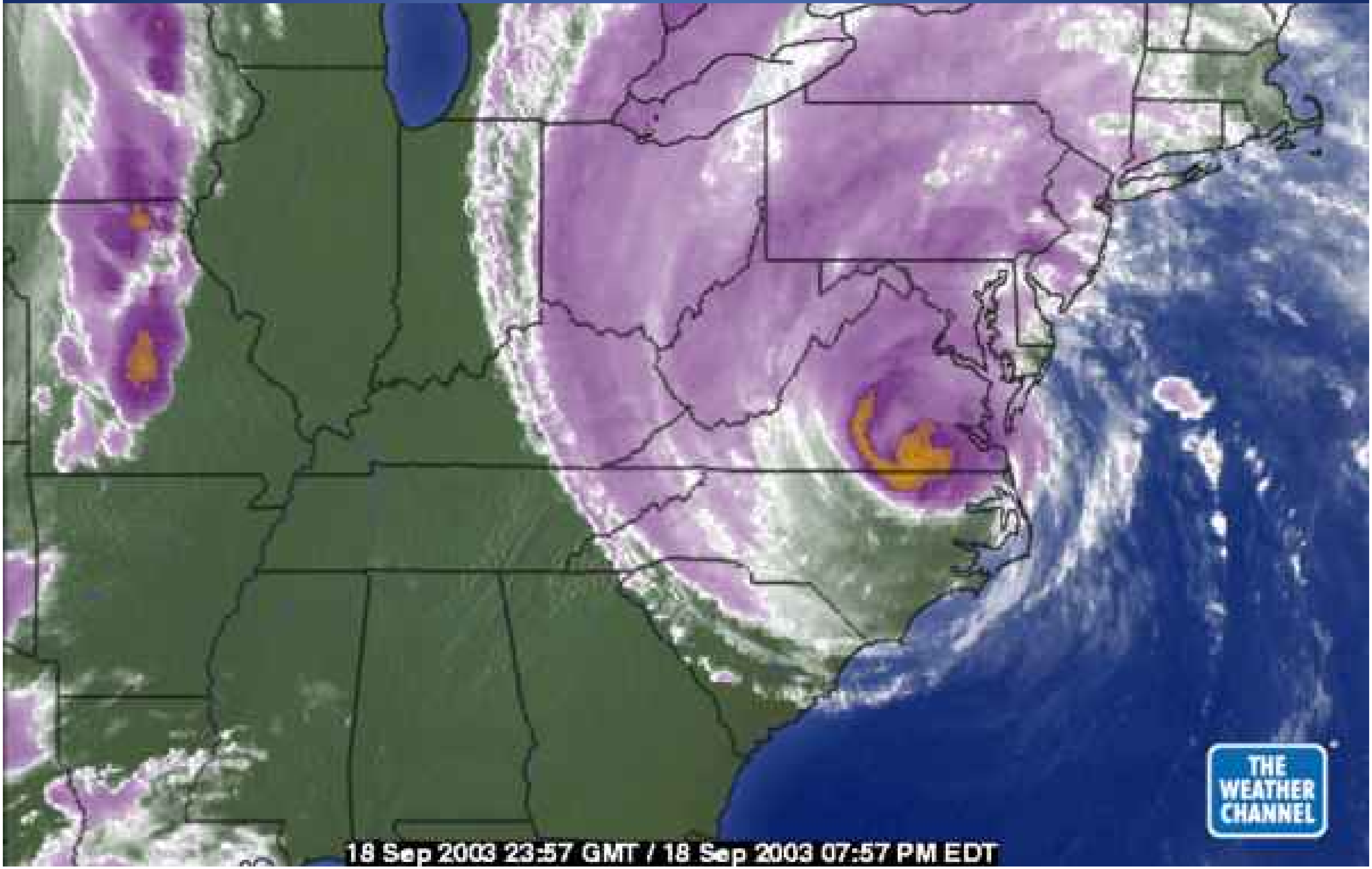


Recent satellite image showing AWC stands (darker images)

Totaling

a few thousand acres

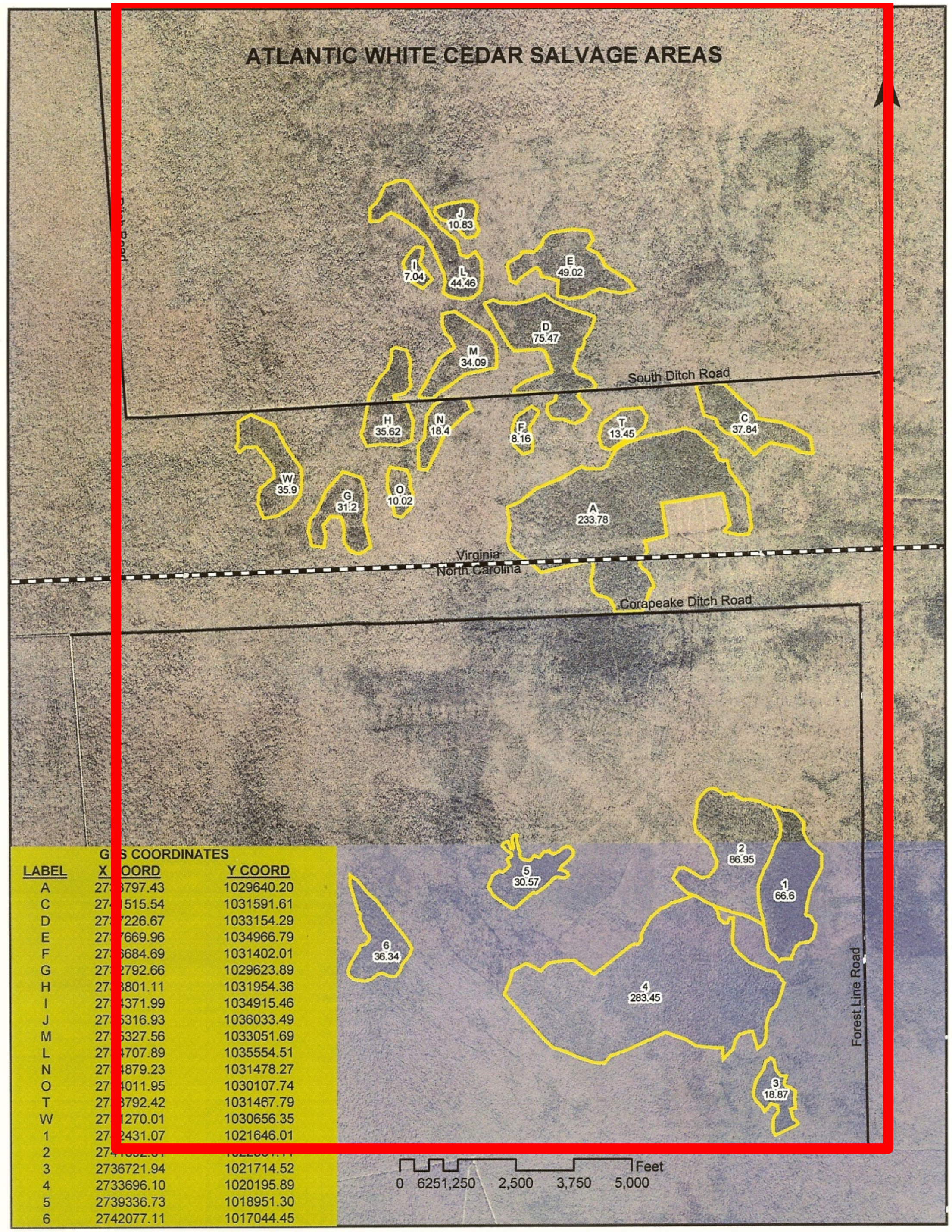
Hurricane Isabel 9/18/03



Damage from Hurricane Isabel

aerial photograph provided by B. Martin

Atlantic White Cedar salvage logging plan for GDS



Perturbation: natural event with which most inhabitants evolved and that causes the temporary loss of the climax plant community.

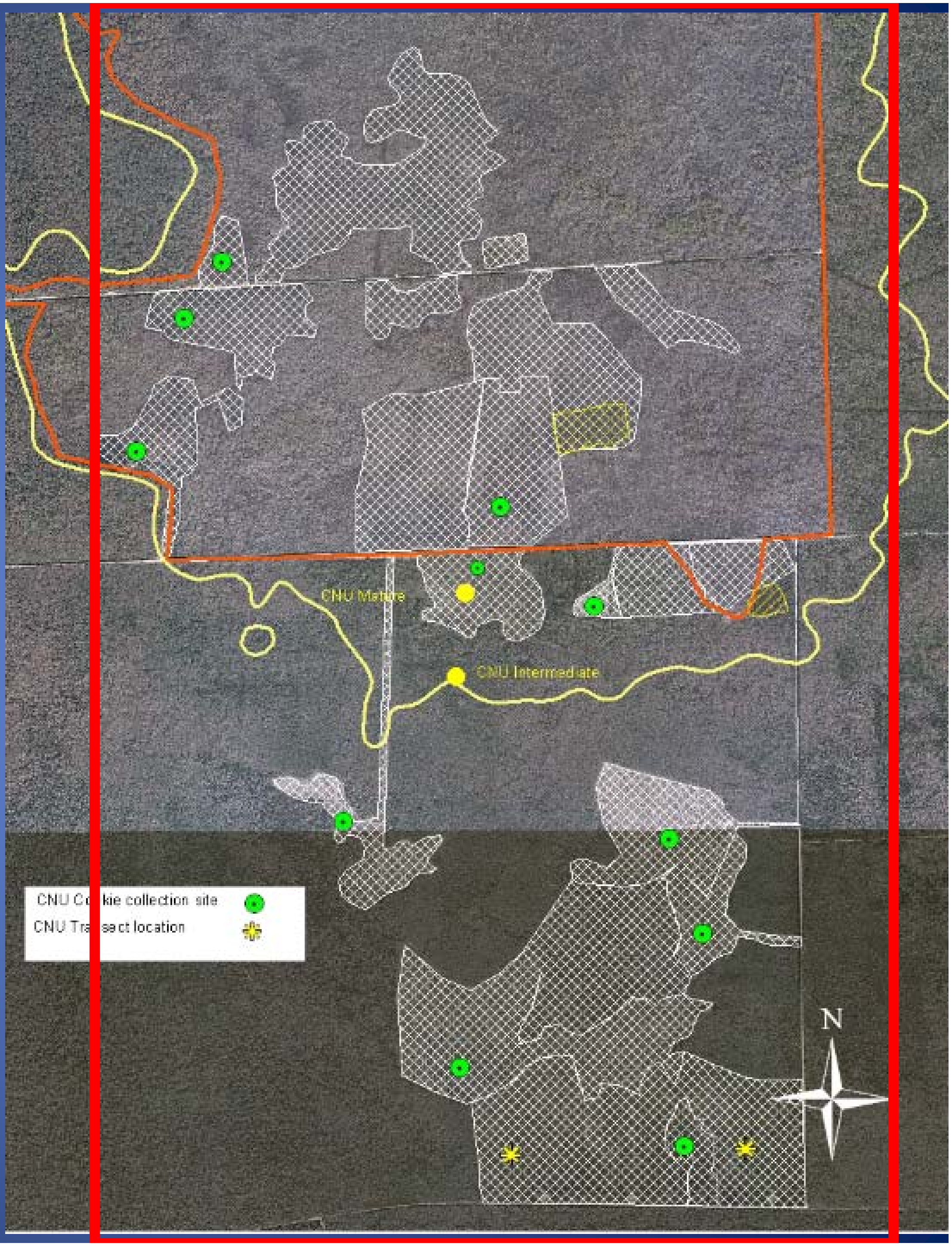
Disturbance: human-induced event that may cause relatively permanent loss of the climax community if the event isn't similar to a perturbation.

Key: fire is a perturbation unless water tables are unnaturally low

Opportunity provided by Hurricane and salvage-logging

Cookie collection locations in GDSNWR

- Previous CNU studies of AWC tree rings were conducted in two stands (yellow circles)
- In this study, 11 stands were sampled (green circles); and 5 were subsequently burned.



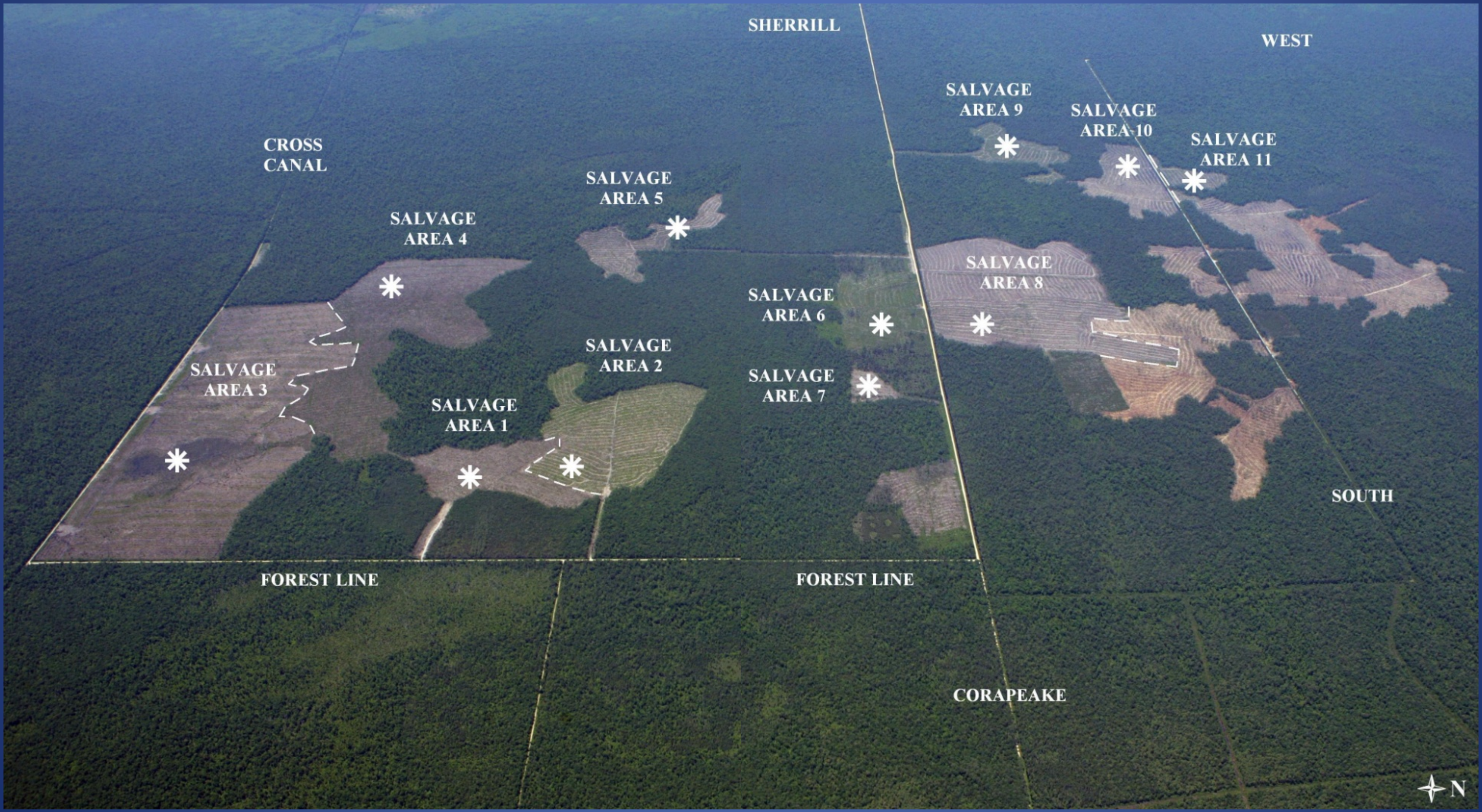
Purpose

- The objective of Craig's study was to:

  utilize dendroclimatic analyses to determine the association between **AWC radial growth** and temperature, precipitation, and drought index and **Lake Drummond** water levels in GDSNWR

Methods

AWC salvage logging areas



AWC salvage logging areas

Stem-cut extraction

Measurement and Cross-dating

- Sanding
- 4 or 5 radial-growth series/ tree
- Assign calendar years
- Visual cross-dating
- Measure ring widths
- 105 ring-width series
- Program COFECHA to ensure cross-dating and measurement accuracy

Program ARSTAN

- Program ARSTAN was used to remove as much non-climatic variation as possible from each ring-width series to maximize the climate signal (ring-width variation common to all trees)

  First detrending to remove variation attributable to **tree age**

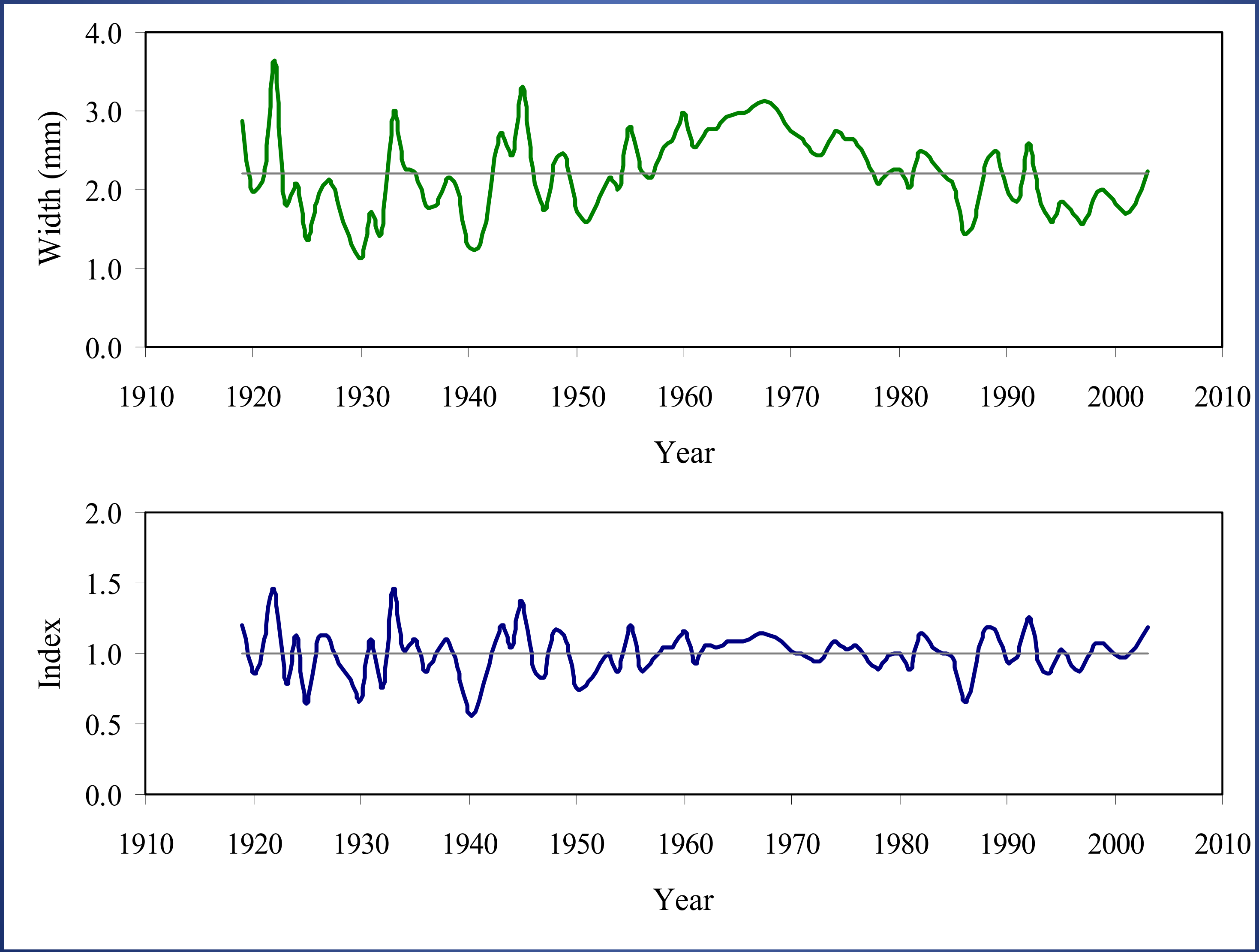
  Second detrending to remove variation attributable to **competition**

  Autoregressive modeling to remove persistence

  Calculation of the RESID chronology

- **Standard procedures for forested sites in the eastern US**

Ring-width measurement and RESID chronologies



RESID chronology quality

- Chronology interval was 1919 through 2003
- SNC Measure of climate-signal strength (COFECHA) 0.644
- RBAR Measure of common variance between ring-width index series that comprised the RESID chronology (ARSTAN) 0.403
- EPS Estimate of the degree to which RESID accurately represented the true chronology (ARSTAN, function of RBAR and sample size) 0.986

Palmer Drought Severity Index

- PDSI calculation is essentially a soil moisture budget
- PDSI values are a function of soil and weather variables and represent relative soil wetness and dryness
- Monthly, regional value
- North Carolina Climate Division 8, northern Coastal Plain (northeast NC)
- Available from 1895
- Positive values indicate moist conditions
- Negative values indicate dry conditions

Precipitation and temperature

- **Precipitation data:**

  total monthly precipitation

  Wallaceton Lake Drummond, VA (less than 10 km from all salvage areas)

- Temperature data:

  mean monthly temperature (daily average, high, and low)

  Elizabeth City, NC (less than 39 km from all salvage areas)

- Temperature and **precipitation data available from 1931**

Climate-radial growth analyses

- **Simple linear correlation analysis was used to:**

  Determine the extent to which indices of the RESID chronology varied with monthly climatic values

  Identify months, seasons, and climatic variables most influential to growth

- Multiple linear regression analysis was used to:

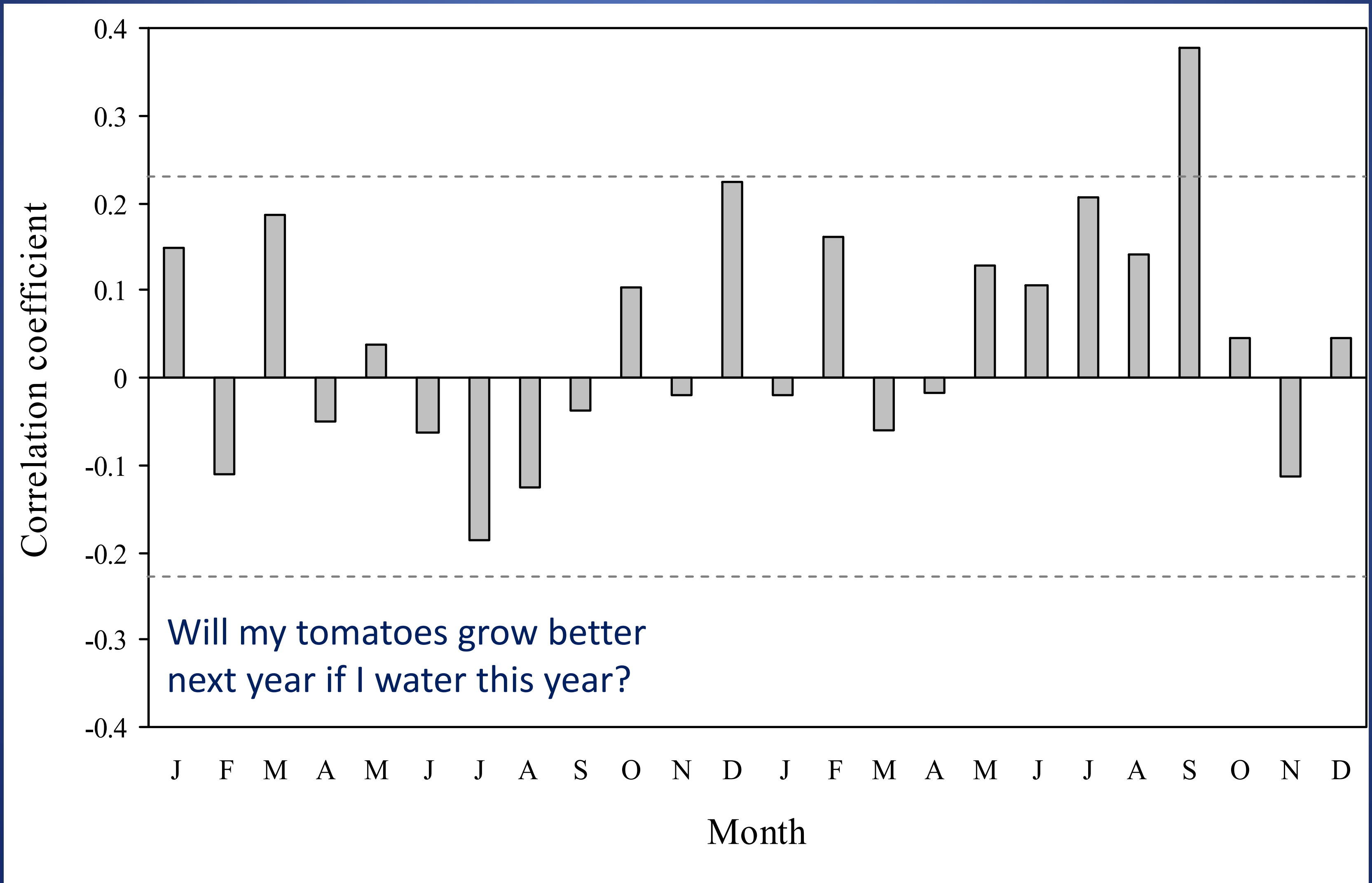
  determine the combination of monthly temperature, precipitation, and PDSI variables that accounted for the greatest amount of ring-width variability

Climate-radial growth analyses

- Program SYSTAT
- Correlations were calculated over a 24-month climate window from previous-year January through current-year December
- Two-tailed hypothesis testing was used
- Significance level for all analyses was 95% ($\alpha = 0.05$)

Results and Discussion

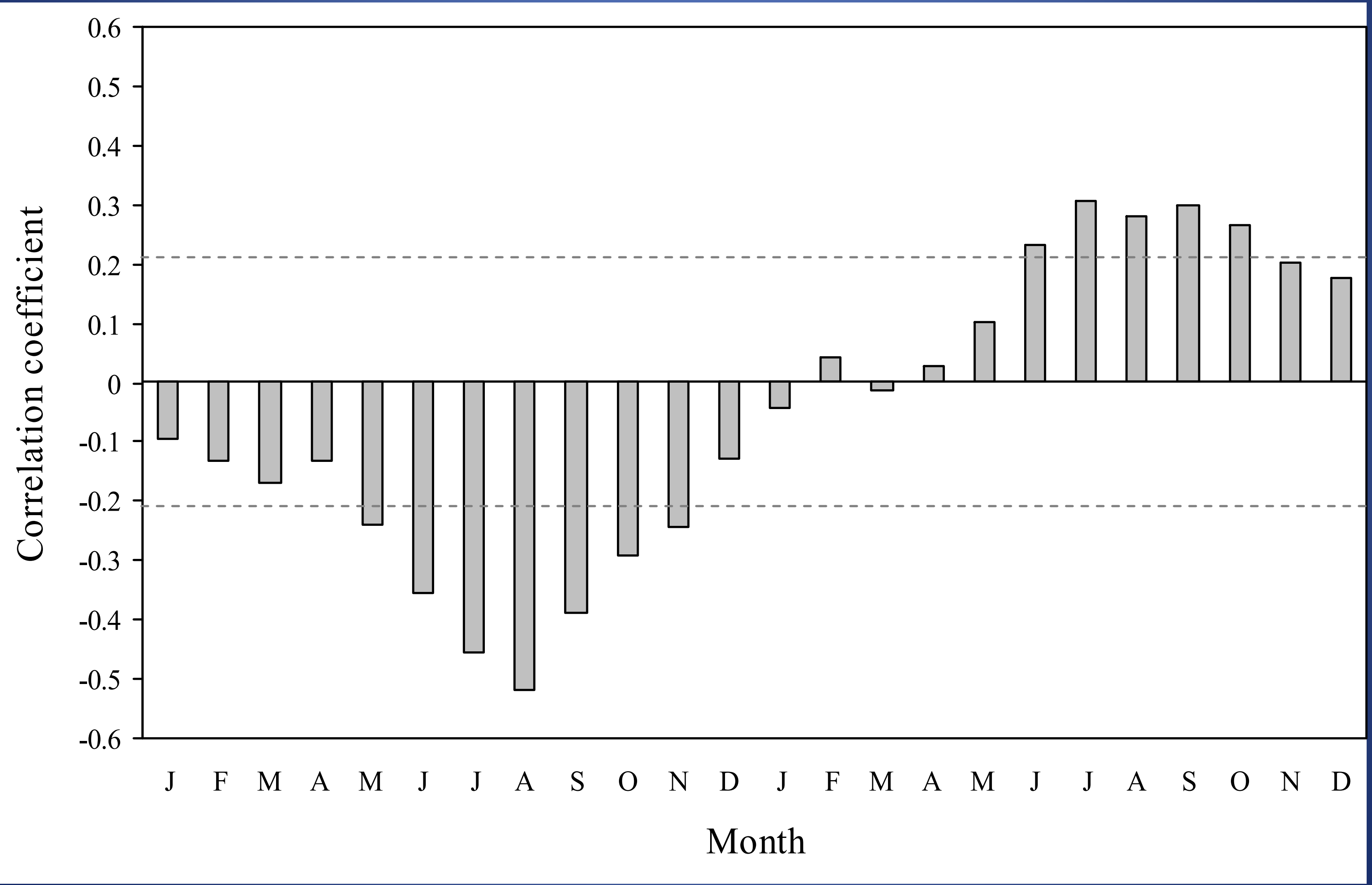
Correlations between RESID and precipitation



Precipitation is a messy parameter.

PDSI is better.

Correlations between RESID and PDSI



Lake Drummond

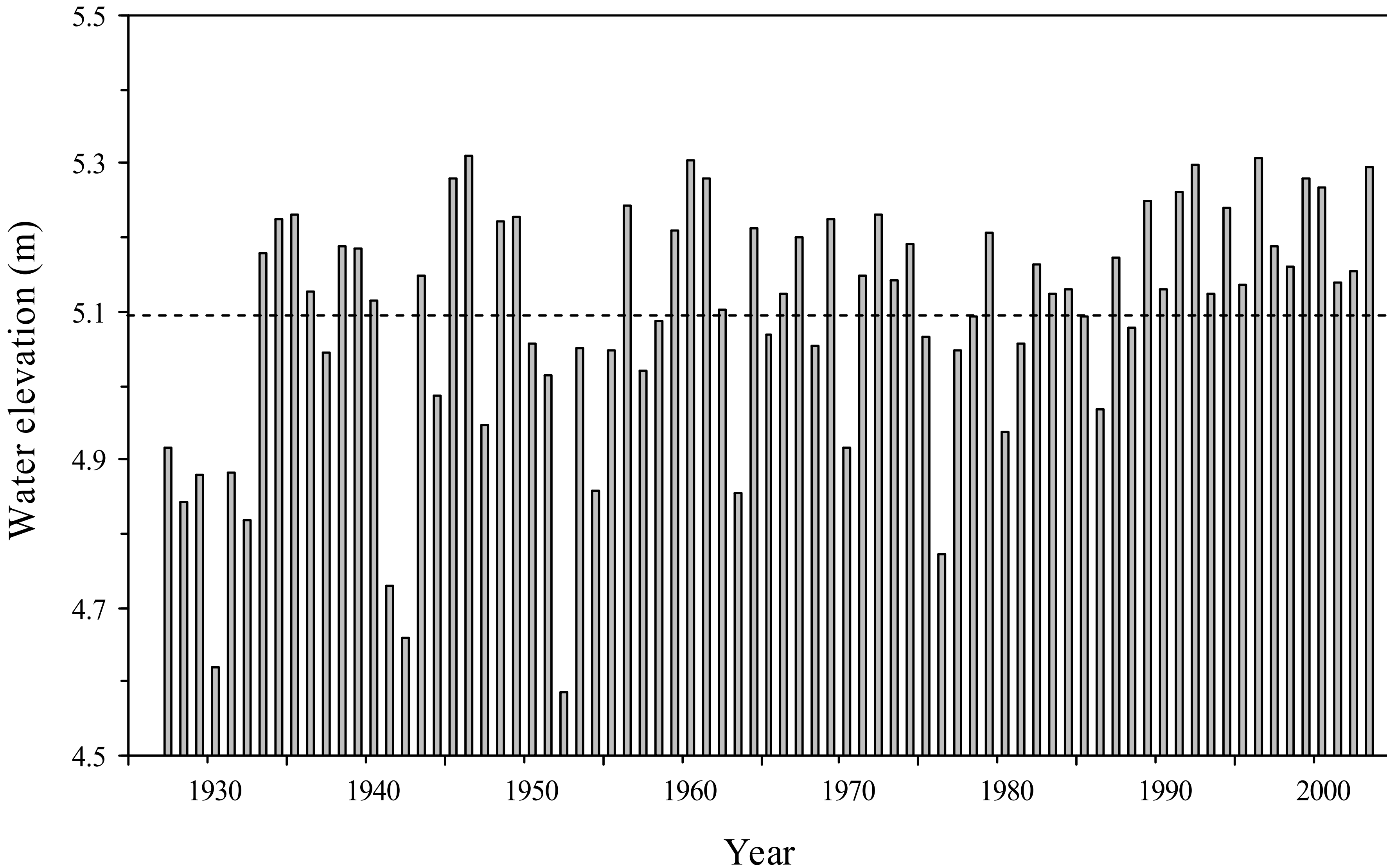
Staff gauge at the Feeder Ditch

Monthly water level data available since 1926

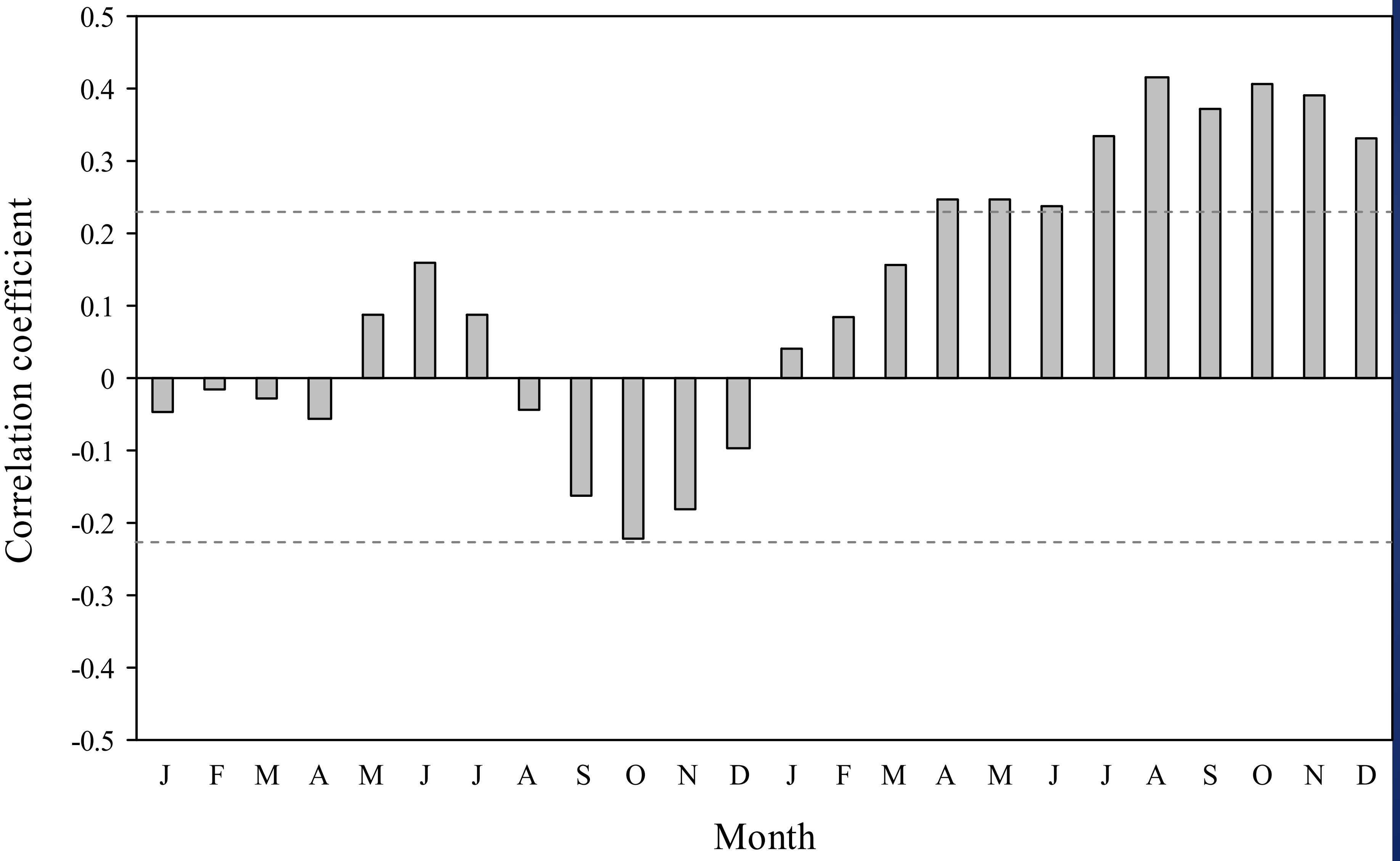
Photo May 2002, courtesy of Norfolk District, Corps of Engineers

Mean Annual Lake Drummond water levels 1927 to 2003

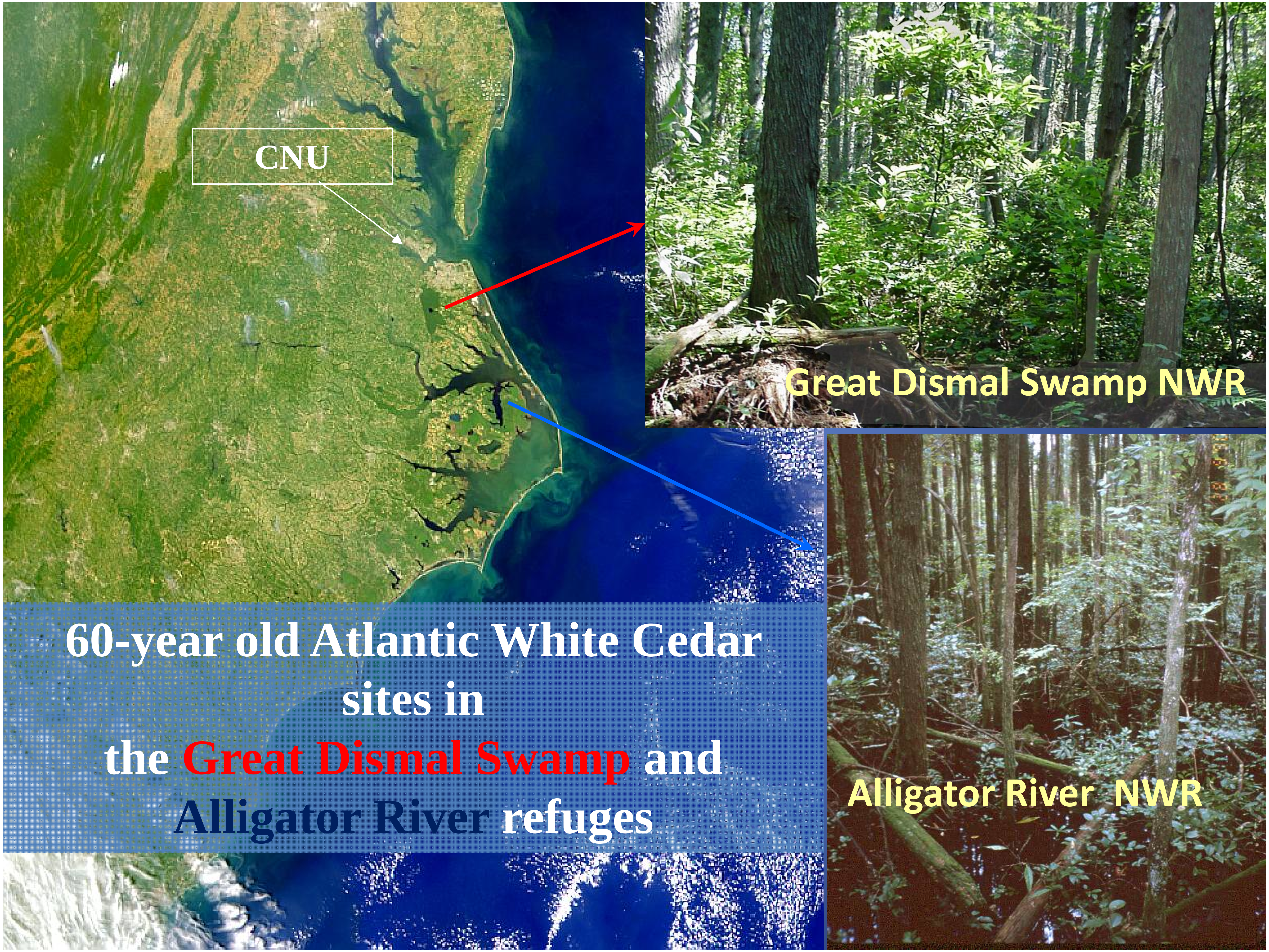
Horizontal line indicates
the mean lake elevation during this period (5.09 m).

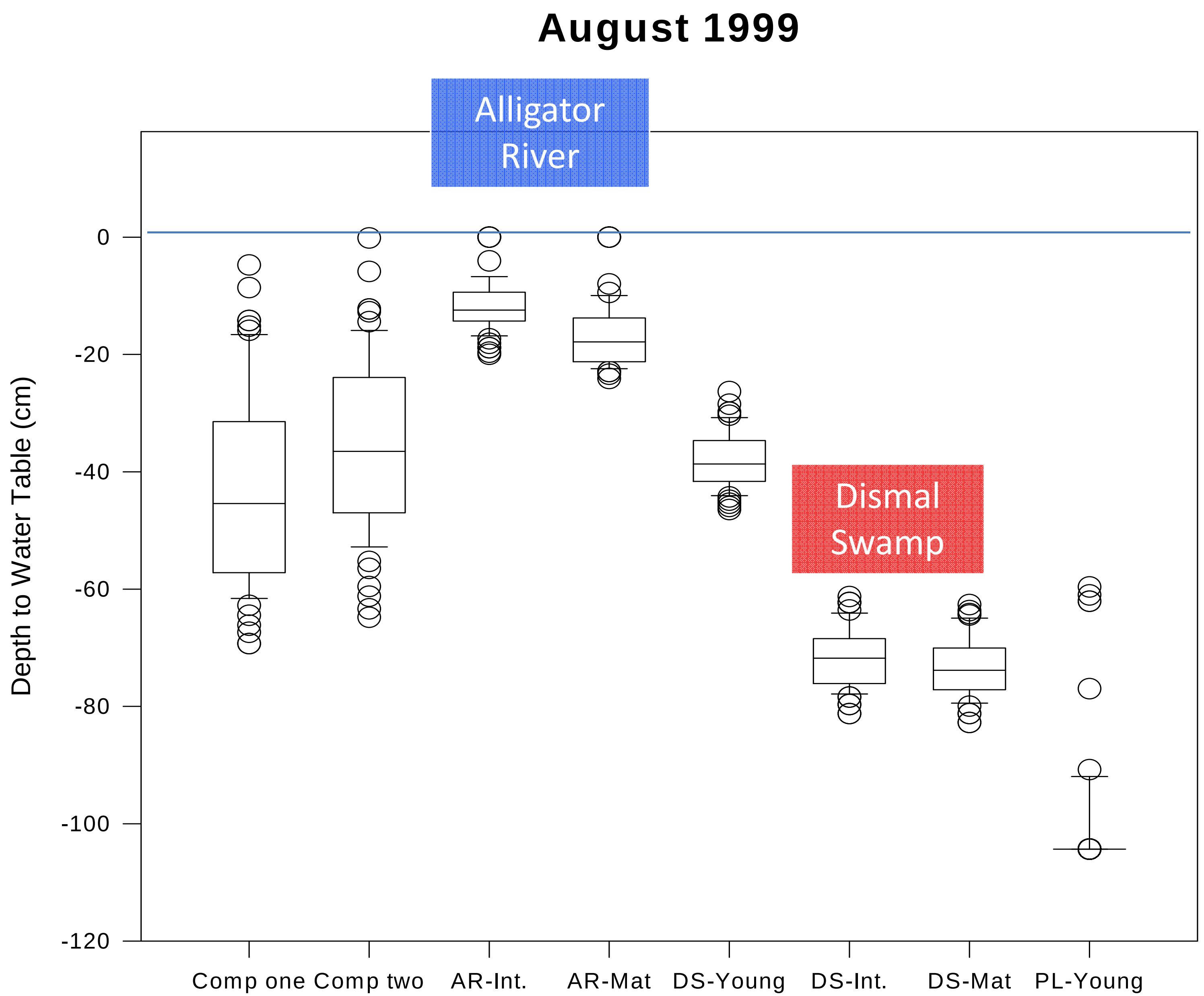


Correlations between RESID and Lake Drummond



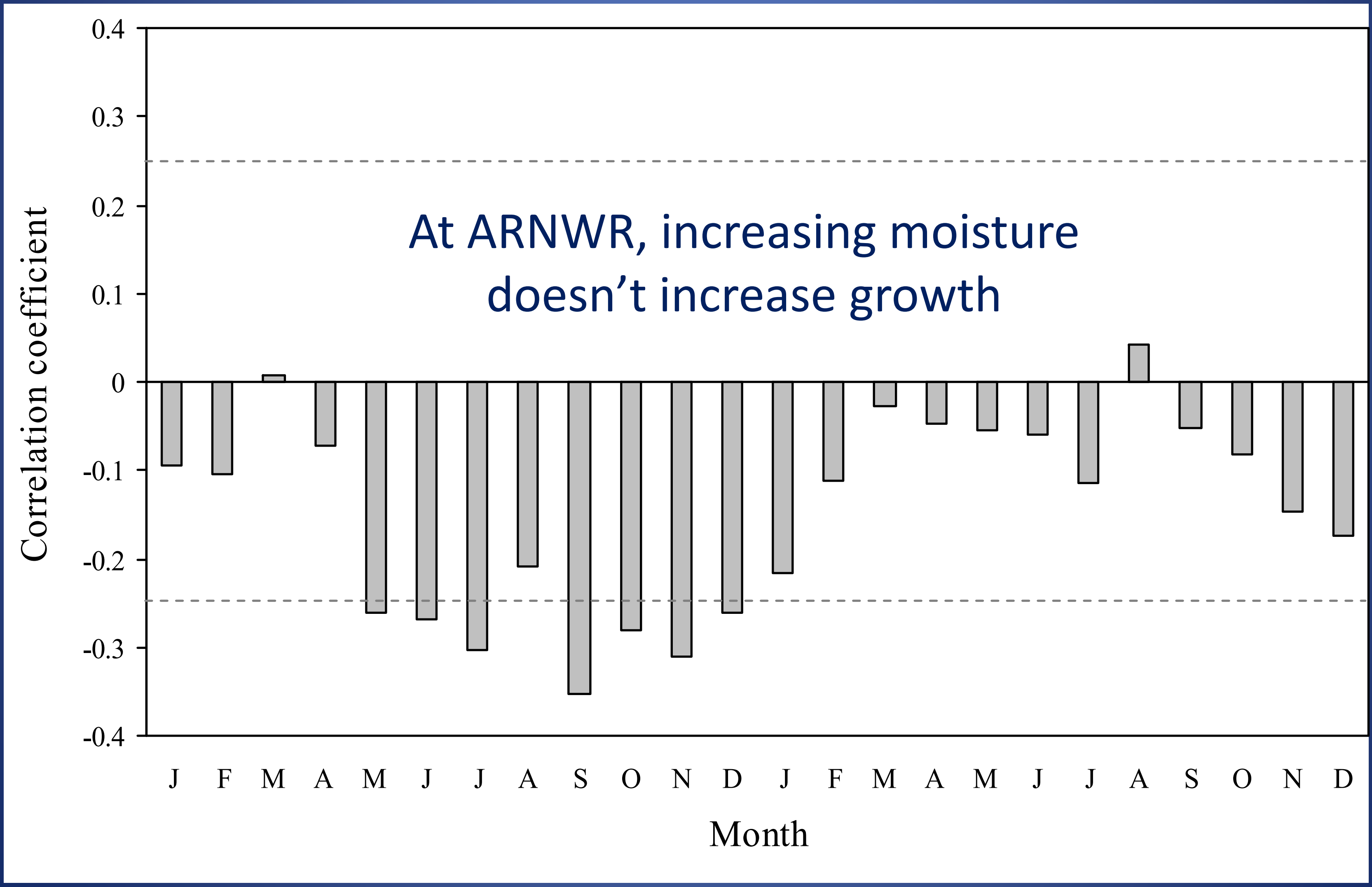
Looking beyond climate signals


CNU
Great Dismal Swamp NWR
Alligator River NWR
60-year old Atlantic White Cedar
sites in
the Great Dismal Swamp and
Alligator River refuges

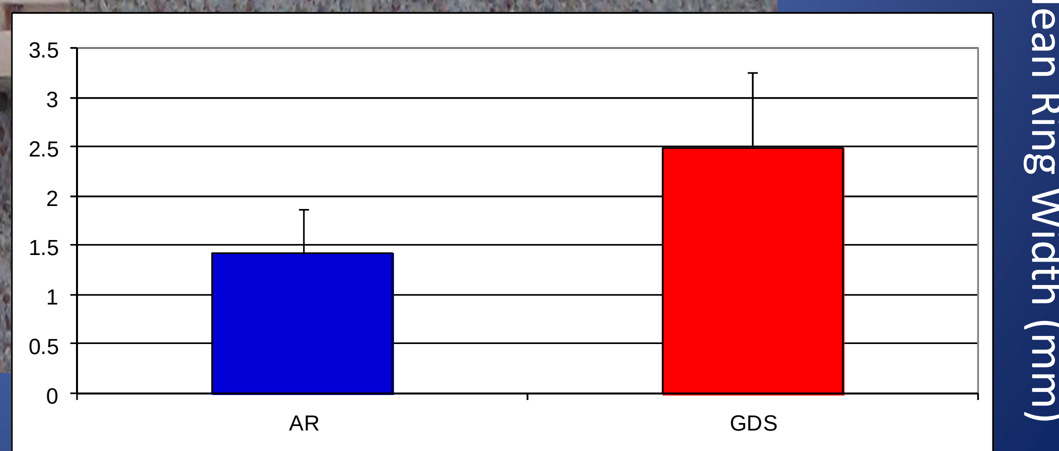


August 1999
Alligator River
Dismal Swamp
Depth to Water Table (cm)
0
-20
-40
-60
-80
-100
-120
Comp one
Comp two
AR-Int.
AR-Mat
DS-Young
DS-Int.
DS-Mat
PL-Young

Correlations between RESID and PDSI in ARNWR
Merry (2005)



AWC grows slower under very poorly drained conditions



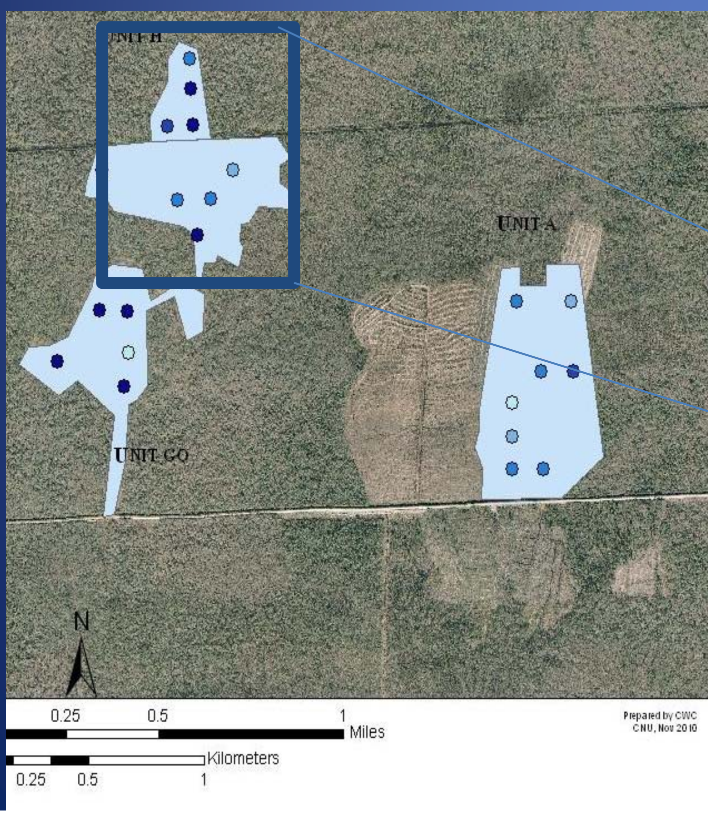
Application
Can tree rings predict these ecosystem services:

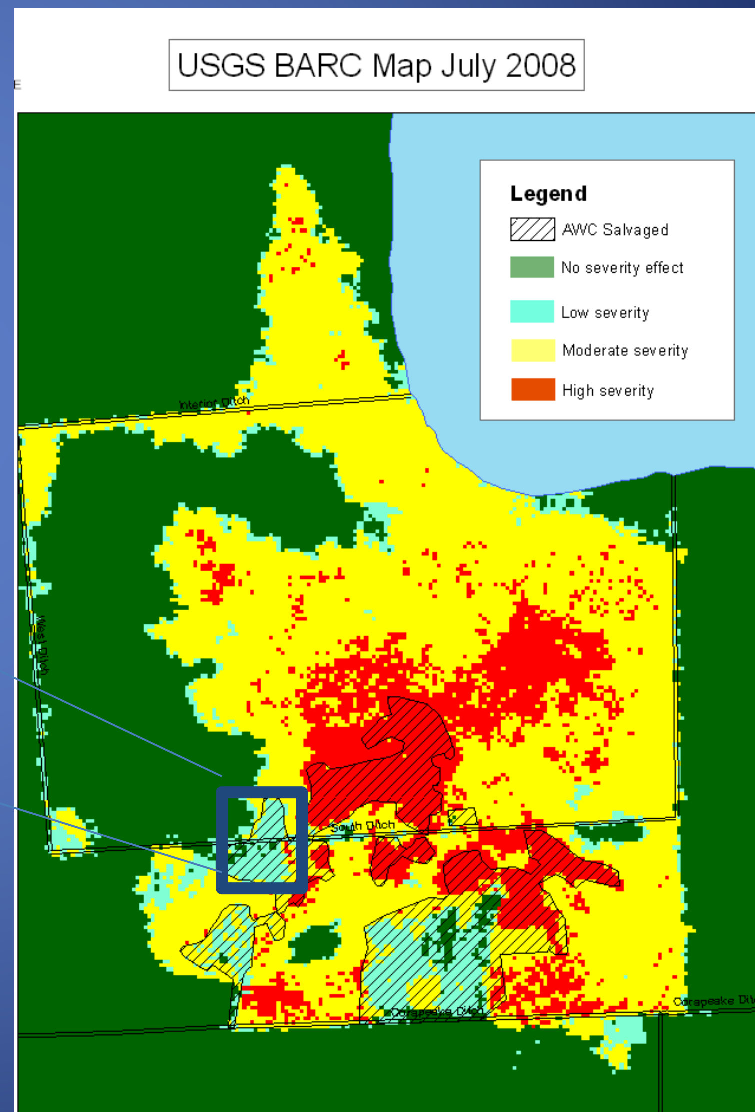
Self-maintenance: regeneration after fire
Carbon sequestration: in peat cores
Nutrient retention and Mercury retention
Wildlife: birds, amphibians, reptiles and mammals

Craig reported that salvage-logging unit HN/HS exhibited the narrowest rings.

The area had some of the lowest PIV (Dark Blue circles)...

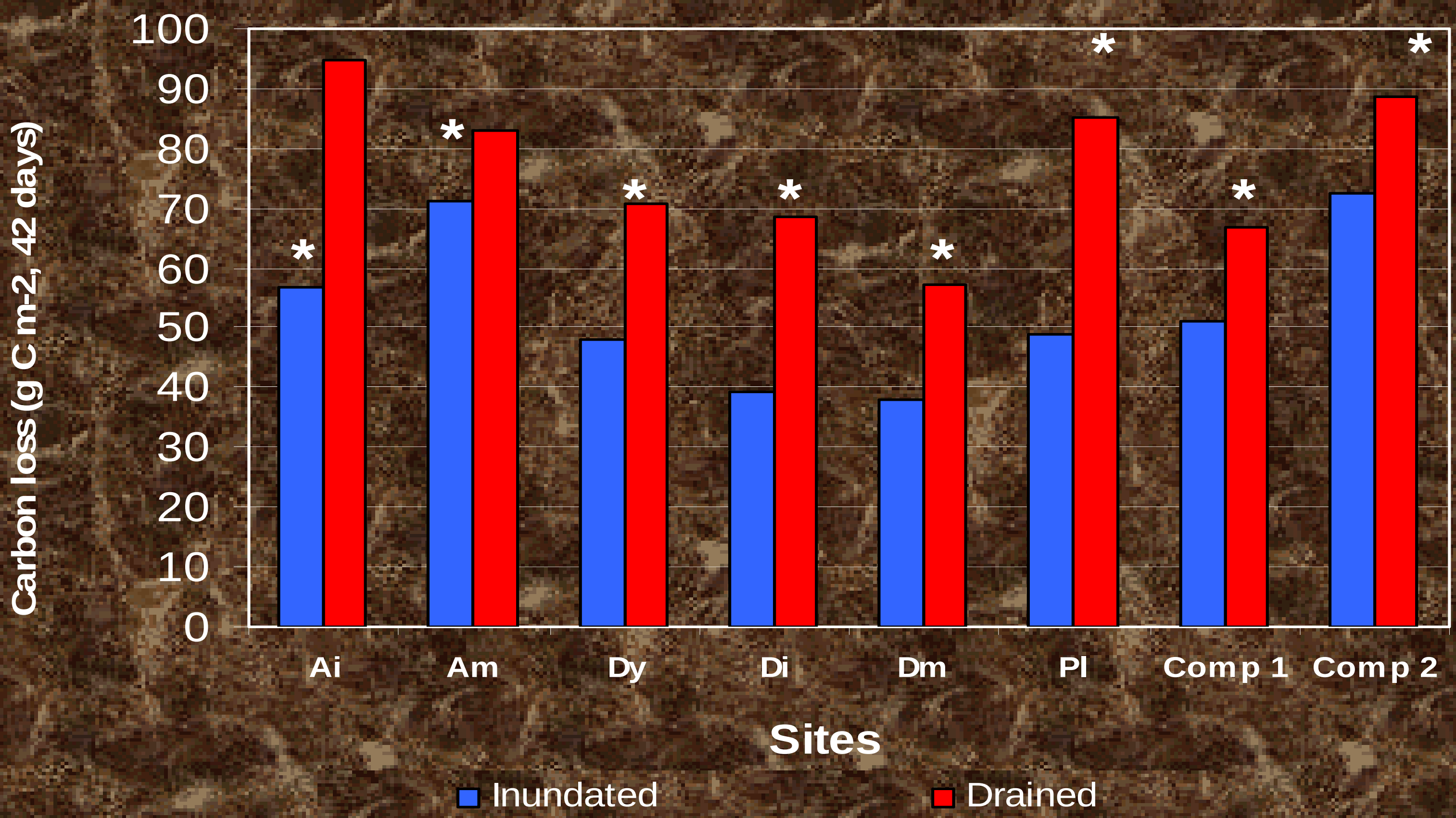
...and least severe fire! Conclusion: best candidate for self-maintenance.





Carbon Sequestration

Mass of carbon lost as carbon dioxide over the 42-day concurrent treatment comparingf the usual field hydrology condition during the growing season (*) and the alternate condition.



Key. Alligator River intermediate (Ai), AR mature (Am), Great Dismal Swamp young (Dy), GDS intermediate (Di), GDS mature (Dm), Pocosin Lakes (Pl), Comprehensive Site 1 (C1, Comp 2 (C2)

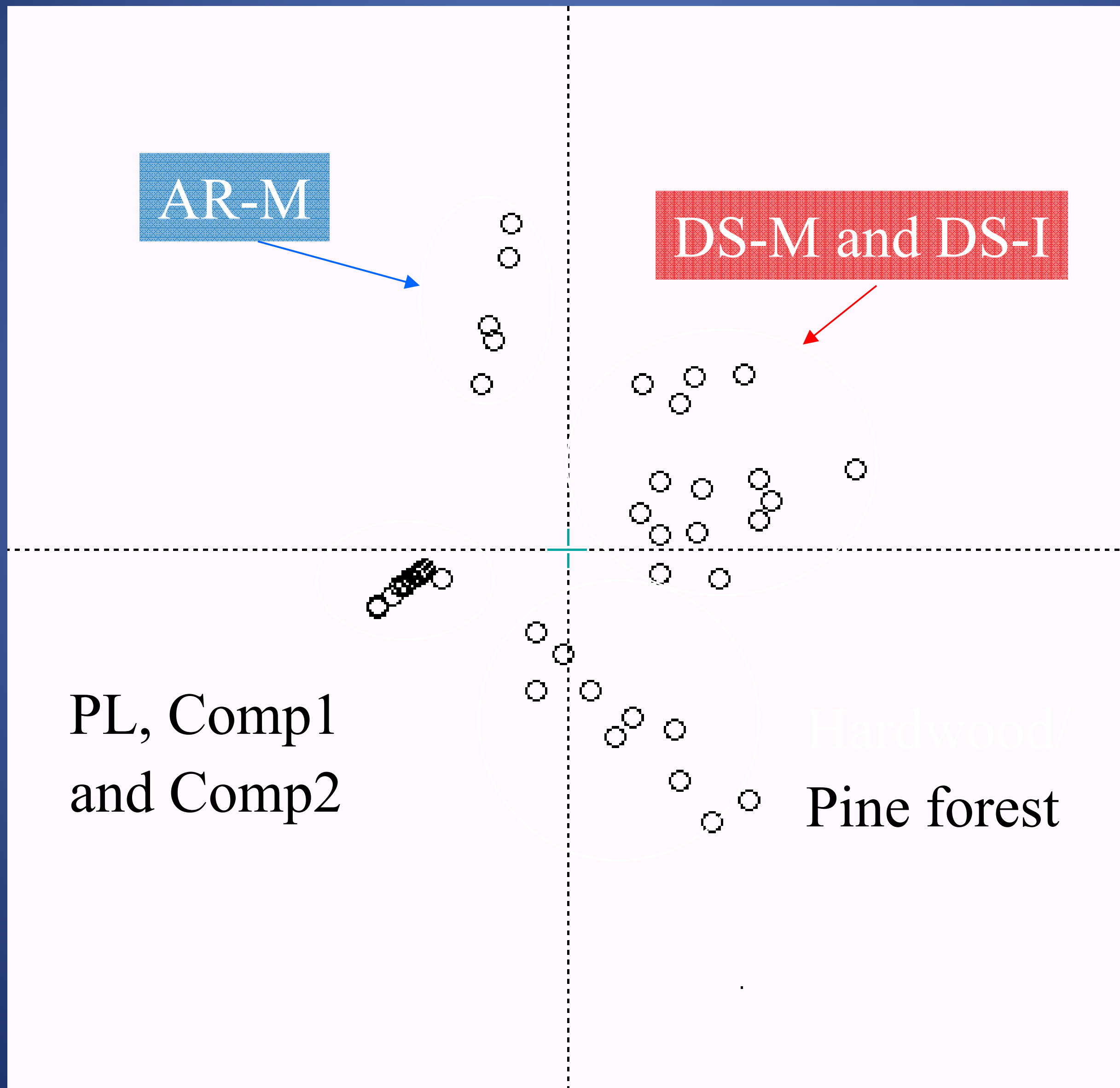
Nutrient retention and
Mercury retention

both reduced by high water tables

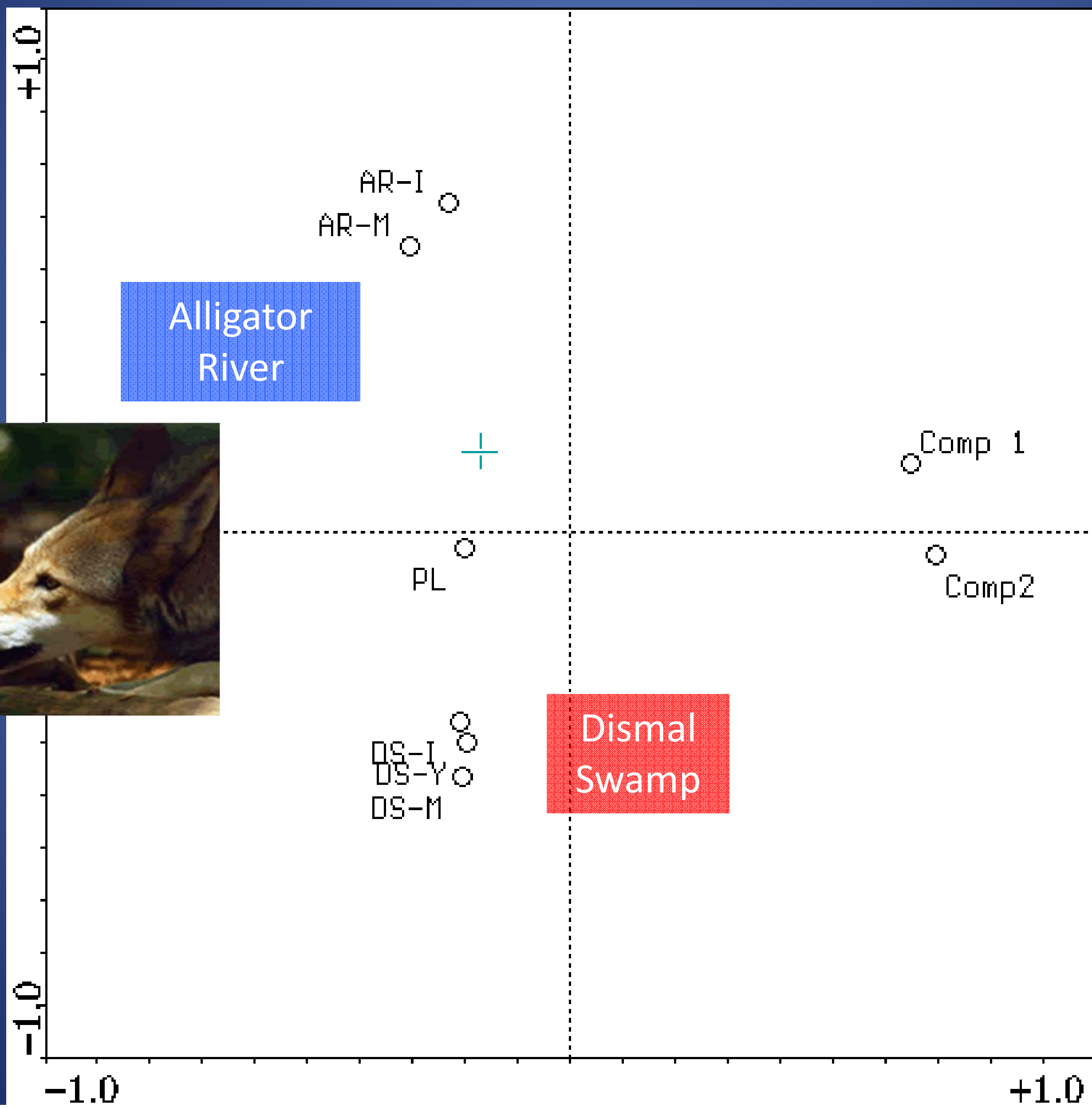
But what about biodiversity?

PCA: Birds (Hester 2003)

Small circles represent study plots. Plots with similar species composition occur nearer to each other on PCA graphs.



PCA: Amphibians, reptiles, & mammals



Can higher water levels fix the Greek financial crisis?

Summary

**By indicating longer-term hydrographs,
tree rings may predict many of peatland functions
known to be guided by hydrology.**

Craig's Acknowledgements

- GDSNWR administration provided access to sites
- GDSNWR staff member, Bryan Poovey, assisted in cookie retrieval and site selection.
- CNU's CWC students assisted in cookie retrieval and CWC provided tree ring equipment and **cookie storage** space.

Acknowledgements

Students

D.A. Brown, Amy Seim, Shana Merry, Craig Patterson, Amber Bradshaw, Erin Bradshaw, Emily Foster, Bayley Cook, Catey Lavagnino, Shawn Wurst, Justin Weiser, Mellony Seidel, Brittany Bowen, Jackie Roquemore, Nathan Evans, Tim Heard, Jolie Harrison, Darren Loomis, Jef DeBerry, Robert Belcher, William Hester, Greg Thompson, Kristen Shacochis, Patty Duttry, Stephanie Moore, Wes Hudson, Mark Kalnins, Jenifer Garda, Stacy Boyles, Mike Harrison, Melissa Kesler, LeRoy Rodgers, Edward Crawford, Stephanie Breeden, Travis Comer, Laura Clark, William Cantillo, Carter Goerger, John Miller, Crystal Levinson, Jessica Campo, Lauren Achtemeir, Dallas Peck, Sam Burks

and

Dr. Neil Pederson, Lomont Doherty Earth Observatory
Dr. Christopher Craft, Indiana University
Dr. Timothy Morgan, Christopher Newport University, retired
Dr. Frank Day, Old Dominion University
Dr. George Webb, Christopher Newport University
Dr. Gary Whiting, Christopher Newport University
Bud Needham, Needham Associates
Steve Martin, US Army Corps of Engineers
Dr. Harold Cones, Christopher Newport University, retired
Dr. George Zimmermann, Stockton University
Chris Lowie, Bryan Poovey, Cindy Land, Fred Wurster GDSNWR
David Norris, VA Dept. of Game and Inland Fisheries
US EPA STAR Grant no. R825799

Acknowledgements continued

Atlantic White Cedar Alliance
was instrumental in gaining the USEPA grant that
provided most of the funding for research presented.

and

AWC Alliance members Aimlee Laderman,
Joy Greenwood and John McCoy for providing sites
should a pending NSF proposal defy the odds.

Nearly half of the data just presented was collected by students who were generally not financially supported.

Their commitment to this ecosystem is an inspiration.

Thank you

Implications for Future Research

- This summer we hope to retrieve cookies from salvage-logging that burned last fall.
  - AWC pollen records date back 6,500 years in GDS and we hope to
    - Contrast Craig's recent ring width findings with older AWC
    - Establish a continuous chronology that would demonstrate pre-ditch ring widths
- This fall we will hear from an NSF proposal that would allow us to work with
  - Dr. Aimlee Laderman in the northeast and John McCoy in Louisiana to tie ring widths to historic water table depths and
    - Risk of seed bank loss and elimination of AWC in event of fire.
    - Carbon condition/potential C emissions from peat.
    - Risk of Mercury export from peat.

AWC-stand hydrology in GDSNWR

- Water table elevation is highest in March, April, and May
- Growing-season soil moisture content is most stable during this time
- As temperature and evapotranspiration increases, drawdown of the water table below the root zone occurs
- In summer and autumn, water table fluctuates in and out of the root zone in response to precipitation and evapotranspiration
- Growing-season soil moisture content is most variable in summer and autumn; rainfall is also most variable at this time of year

Current-year summer and autumn soil moisture

- These results indicate that high root-zone soil moisture content in current-year summer and autumn enhanced AWC radial growth
- These results are more typically associated with mesic sites than wetlands
- Even in spring, there was little evidence that root-zone soil moisture content was excessive to the extent that annual radial growth was limited
- In GDSNWR, duration of soil saturation in the root zone during the growing season is usually short
- Further evidence that drainage has led to a progressive drying of GDS

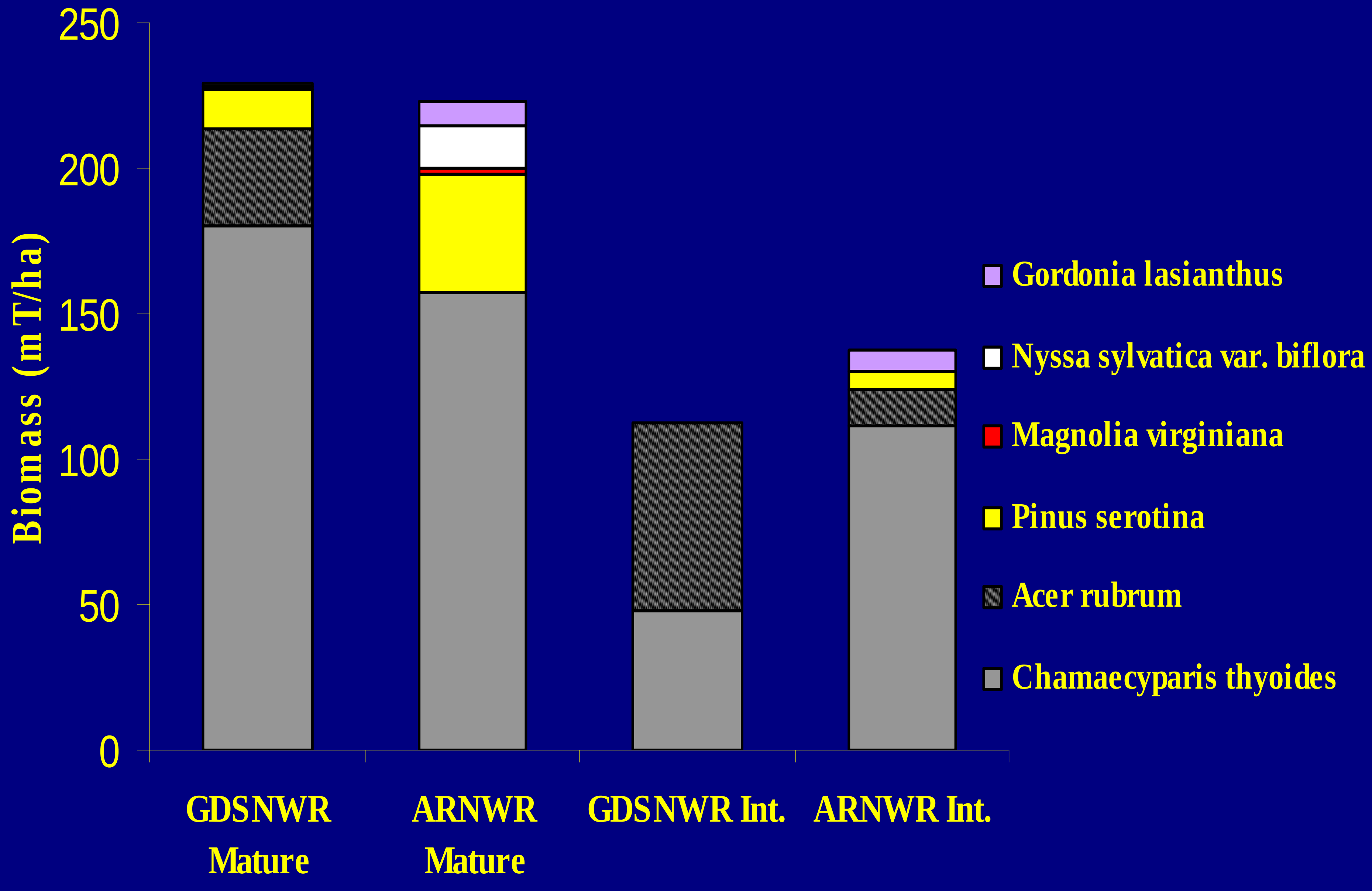
Comparison of GDSNWR and ARNWR models

- Correlation results depicting the soil moisture response of AWC in GDSNWR and ARNWR represent models from which comparisons with future studies can be made
- AWC stands in ARNWR are reference sites for peatland AWC restoration
- The ARNWR model represents the soil moisture-radial growth response from a site with a hydrologic regime conducive to AWC self-maintenance
- The GDSNWR model represents the soil-moisture-radial growth response from stands with a hydrologic regime less favorable for AWC
- These models can help with interpreting correlation results from relict AWC in GDS and evaluating the performance of AWC restoration sites

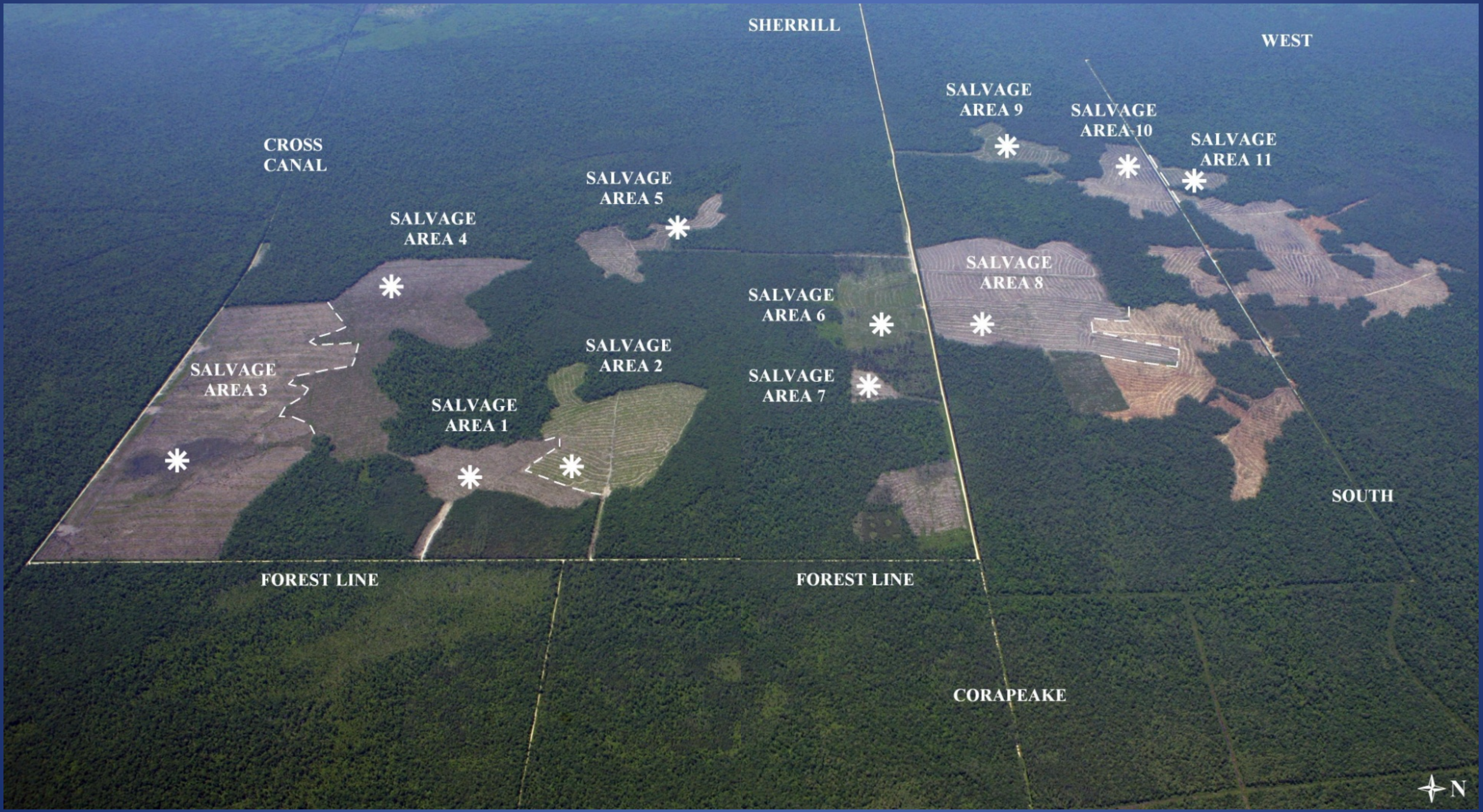
Site selection for AWC restoration

- Self-maintaining AWC stands are often characterized by low rates of radial growth due to a high and stable water table and / or high stem density
- These conditions are less favorable to germination and growth of hardwood species and decrease the likelihood of fires consuming surface peat
- High rates of radial growth may be indicative of low stand density and / or a low and fluctuating water table
- Are there significant differences in AWC radial growth in GDSNWR stands?
- Significantly smaller ring widths in salvage areas 2 and 11

Aboveground Biomass Components



AWC restoration



Important findings

- AWC radial growth in GDSNWR is sensitive to soil moisture in summer and autumn of the previous year and current year
- A relatively strong negative correlation between previous-year soil moisture and ring width is an uncommon result, but it appears to be a result shared by the few AWC radial-growth studies that have been completed
- Differences in growth allocation, carbon storage, shoot growth, and nutrient dynamics in wet and dry years may have a strong influence on peatland AWC radial growth
- Positive correlations between current-year soil moisture may be indicative of a hydrologic regime not conducive to peatland AWC self-maintenance
- The GDSNWR and ARNWR soil moisture-radial growth models should be very helpful in future tree-ring studies and restoration efforts

References

Akerman A. 1923. The white cedar of the Dismal Swamp. Charlottesville (VA): Virginia Geological Commission. Virginia Forestry Publication No. 30.

Alley WM. 1984. The Palmer Drought Severity Index: limitations and assumptions. Journal of Climate and Applied Meteorology. 23:1100-1109.

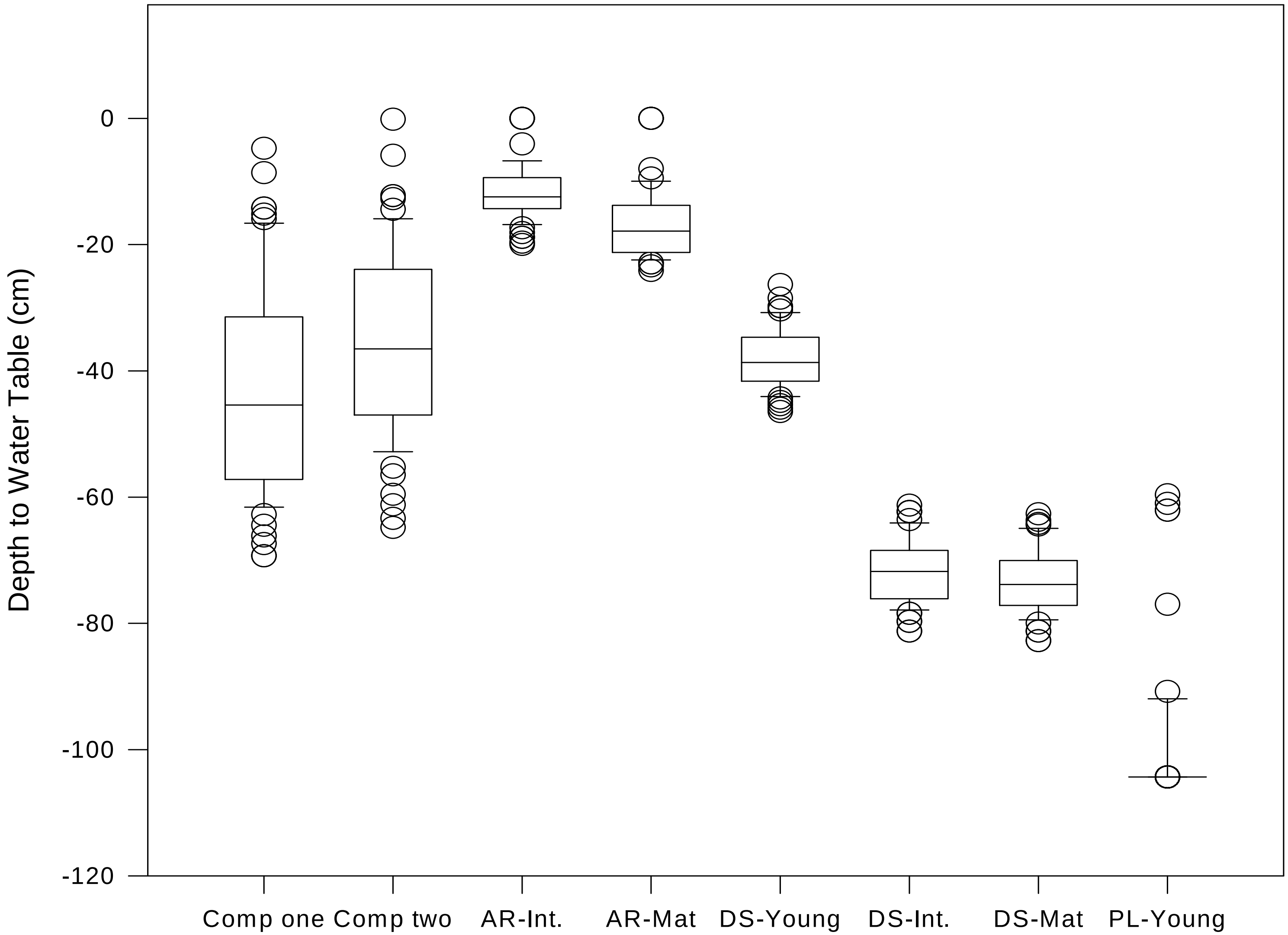
Atkinson RB. 2001. Atlantic white cedar swamp restoration: monitoring ecosystem services and self-maintenance. Newport News (VA): Christopher Newport University. Unpublished final report. Sponsored by the US EPA National Center for Environmental Research.

Atkinson RB, DeBerry JW, Loomis DT, Crawford ER, Belcher RT. 2003a. Water tables in Atlantic white cedar swamps: implications for restoration. In: Atkinson RB, Belcher RT, Brown DA, Perry JE, editors. Atlantic white cedar restoration ecology and management: proceedings of a symposium. 2000 May 31-Jun 2; Christopher Newport University, Newport News, VA. Gloucester Point (VA): VIMS Publications Center. p. 137-150.

Atkinson RB, Morgan TE, Belcher RT, Brown DA. 2003b. The role of historical inquiry in the restoration of Atlantic white cedar swamps. In: Atkinson RB, Belcher RT, Brown DA, Perry JE, editors. Atlantic white cedar restoration ecology and management: proceedings of a symposium. 2000 May 31-Jun 2; Christopher Newport University, Newport News, VA. Gloucester Point (VA): VIMS Publications Center. p. 43-53.

Belcher RT, Poovey B. 2009. Atlantic white cedar salvage efforts in the Great Dismal Swamp following Hurricane Isabel. In: Zimmermann GL, editor. Proceedings of the ecology and management of Atlantic white-cedar: symposium 2006 [Internet]. 2006 Jun 6-8; Atlantic City, NJ. [cited 2010 Oct 16]. p. 59-70. Available from: http://loki.stockton.edu/~wcedars.

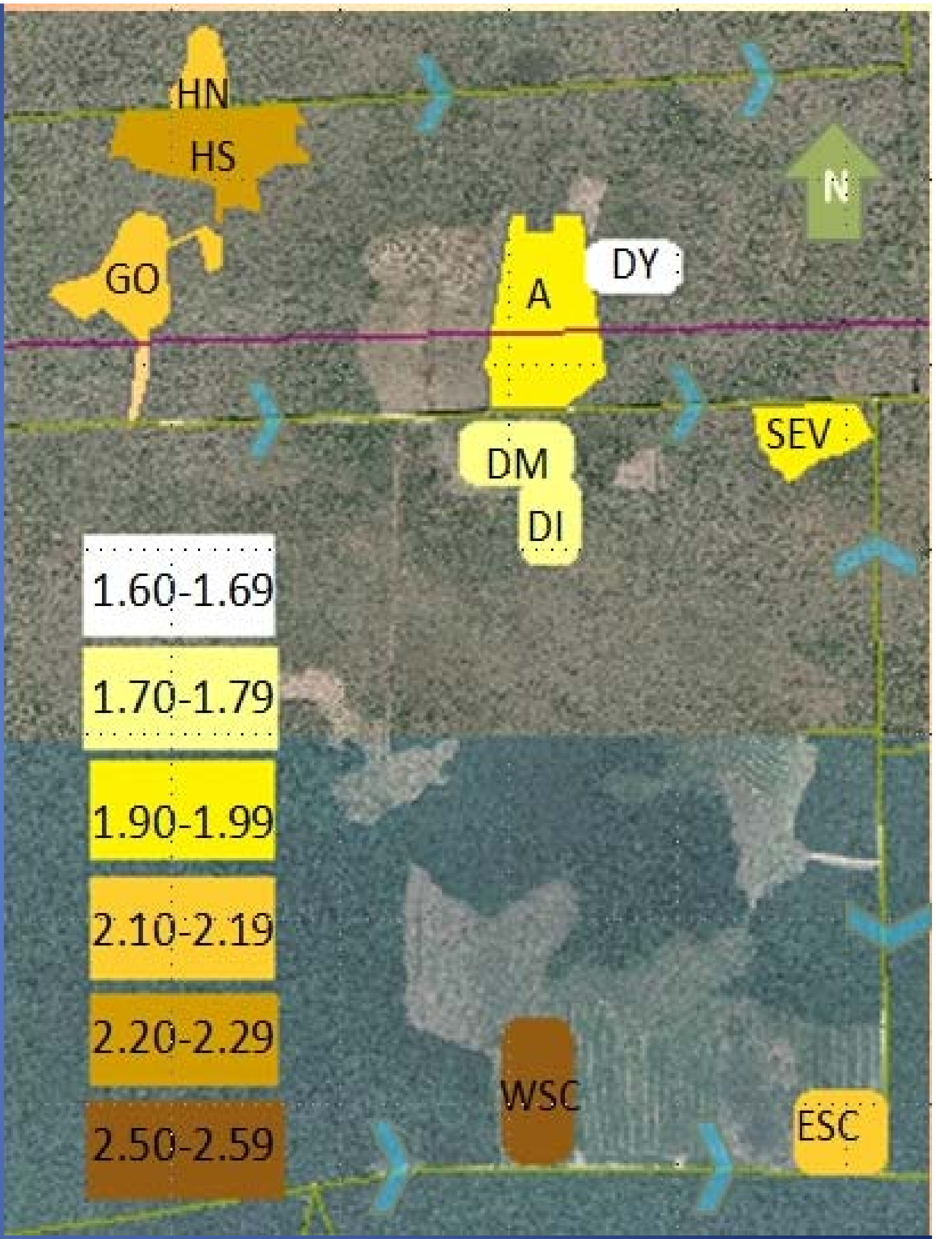
August 1999



Depth to Water Table (cm)
0
-20
-40
-60
-80
-100
-120
Comp one
Comp two
AR-Int.
AR-Mat
DS-Young
DS-Int.
DS-Mat
PL-Young

Implications

- And HN had the smallest ring widths in spite of having generally higher soil N content.



Craig's Acknowledgements

- GDSNWR administration provided access to sites
- GDSNWR staff member, Bryan Poovey, assisted in cookie retrieval and site selection.
- CNU CWC assisted in cookie retrieval and provided tree ring equipment and cookie storage space.

Lastly

- CWC will be addressing the effect of new water control structures on vegetation and potential carbon emissions.
- Thank you

References

Berkeley E, Berkeley D. 1976. Man and the Great Dismal. Virginia Journal of Science. 27:141-171.

Beven J, Cobb H. 2004. Tropical cyclone report: Hurricane Isabel [Internet]. Miami (FL): National Weather Service, National Hurricane Center. [cited 2010 Sep 29]. Available from: http://www.nhc.noaa.gov/2003isabel.shtml.

Bhuta AAR, Kennedy LM, Pederson N. 2009. Climate-radial growth relationships of northern latitudinal range margin longleaf pine (*Pinus palustris* P. Mill.) in the Atlantic Coastal Plain of southeastern Virginia. Tree-ring Research. 65(2):105-115.

Brady NC, Weil RR. 2002. The nature and property of soils. 13th ed. Upper Saddle River (NJ): Prentice Hall.

Bridgham SD, Richardson CJ. 2003. Endogenous versus exogenous nutrient control over decomposition and mineralization in North Carolina peatlands. Biogeochemistry. 65:151-178.

Carter AR. 1987. Cedar restoration in the Dismal Swamp of Virginia and North Carolina. In: Laderman AD, editor. Atlantic white cedar wetlands. Boulder (CO): Westview Press. p. 323-325.

Carter V, Garrett MK, Shima L, Gammon P. 1977. The Great Dismal Swamp: management of a hydrologic resource with the aid of remote sensing. Water Resources Bulletin. 13(1):1-12.

Carter V, Gammon PT, Garrett MK. 1994. Ecotone dynamics and boundary determination in the Great Dismal Swamp. Ecological Applications. 4(1):189-203.

References

Cook ER. 1981. A dendrochronological study of drought in the Hudson Valley, New York. In: Feret PP, Sharik TL, editors. Dendrology in the eastern deciduous forest biome: conference proceedings. 1979 Sep 11-13; Virginia Polytechnic Institute and State University, Blacksburg, VA. p. 133-141. Publication No. FWS-2-80.

Cook ER. 1985. A time series analysis approach to tree ring standardization [dissertation]. Tucson (AR): University of Arizona.

Cook ER. 1987. The decomposition of tree-ring series for environmental studies. Tree-ring Bulletin. 47:37-59.

Cook ER, Nance WL, Krusic PJ, Grissom J. 1998. Modeling the differential sensitivity of loblolly pine to climatic change using tree rings. In: Mickler RA, Fox S, editors. The productivity and sustainability of southern forest ecosystems in a changing environment. New York (NY): Springer-Verlag. p. 717-739.

Cook ER, Pederson N. 2011. Uncertainty, emergence, and statistics in dendrochronology. In: Hughes MK, Swetnam TW, Diaz HF, editors. Dendroclimatology: progress and prospects. New York (NY): Springer Science and Business Media. p. 77-112.

Copenheaver CA, Kyle KH, Stevens GN, Kamp MH. 2005. Comparing *Juniperus virginiana* tree-ring chronologies from forest edge vs. forest interior positions in the Cedars Natural Area Preserve in Virginia, USA. Dendrochronologia. 23:39-45.

Dang QL, Lieffers VJ. 1989. Climate and annual ring growth of black spruce in some Alberta peatlands. Canadian Journal of Botany. 67:1885-1889.

References

Daniel CC III. 1981. Hydrology, geology, and soils of pocosins: a comparison of natural and altered systems. In: Richardson CJ, editor. Pocosin wetlands. Stroudsburg (PA): Hutchinson Ross Publishing Company. p. 69-108.

Day FP Jr. 1982. Litter decomposition rates in the seasonally flooded Great Dismal Swamp. Ecology. 63(3):670-678.

Day FP Jr. 1985. Tree growth rates in the periodically flooded Great Dismal Swamp. Castanea. 50(2):89-95.

Day FP Jr. 1987. Production and decay in a *Chamaecyparis thyoides* swamp in southeastern Virginia. In: Laderman AD, editor. Atlantic white cedar wetlands. Boulder (CO): Westview Press. p. 123-132.

Day FP Jr, West SK, Tupacz EG. 1988. The influence of ground-water dynamics in a periodically flooded ecosystem, the Great Dismal Swamp. Wetlands. 8:1-13.

Day FP Jr, Megonigal JP. 1993. The relationship between variable hydroperiod, production allocation, and belowground organic turnover in forested wetlands. Wetlands. 13(2):115-121.

Day FP Jr, Megonigal JP. 2000. Plant organic matter dynamics in the Dismal Swamp. In: Rose RK, editor. The natural history of the Great Dismal Swamp. Madison (WI): Omni Press. p. 51-57.

Dean GW. 1969. Forests and forestry in the Dismal Swamp. Virginia Journal of Science. 20(4):166-173.

References

DeBerry JW, Belcher RT, Loomis DT, Atkinson RB. 2003. Comparison of aboveground structure of four Atlantic white cedar swamps. In: Atkinson RB, Belcher RT, Brown DA, Perry JE, editors. Atlantic white cedar restoration ecology and management: proceedings of a symposium. 2000 May 31-Jun 2; Christopher Newport University, Newport News, VA. Gloucester Point (VA): VIMS Publications Center. p. 67-80.

Dudek DM, McClenahen JR, Mitsch WJ. 1998. Tree growth responses of *Populus deltoides* and *Juglans nigra* to streamflow and climate in a bottomland hardwood forest in central Ohio. American Midland Naturalist. 140(2):233-244.

Fritts HC. 1976. Tree rings and climate. New York (NY): Academic Press.

Fritts HC, Hughes MK, Milsom SJ. 1982. The climate-growth response. In: Hughes MK, Kelly PM, Pilcher JR, LaMarche VC Jr, editors. Climate from tree rings. Cambridge (GB): Cambridge University Press. p. 33-38.

Frost CC. 1987. Historical overview of Atlantic white cedar in the Carolinas. In: Laderman AD, editor. Atlantic white cedar wetlands. Boulder (CO): Westview Press. p. 257-264.

Golet FC, Lowry DJ. 1987. Water regimes and tree growth in Rhode Island Atlantic white cedar swamps. In: Laderman AD, editor. Atlantic white cedar wetlands. Boulder (CO): Westview Press. p. 91-110.

Gomez MM, Day FP Jr. 1982. Litter nutrient content and production in the Great Dismal Swamp. American Journal of Botany. 69(8):1314-1321.

Gower ST, Isebrands JG, Sheriff DW. 1995. Carbon allocation and accumulation in conifers. In: Smith WK, Hinckley TM, editors. Resource physiology of conifers: acquisition, allocation, and utilization. San Diego (CA): Academic Press. p. 217-254.

References

Grissino-Mayer HD. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-ring Research. 57(2):205-221.

Hayes MJ. 1998. Drought indices [Internet]. Lincoln (NE): National Drought Mitigation Center, University of Nebraska-Lincoln. [cited 2010 Aug 22]. Available from: http://www.drought.unl.edu.

Henderson JP, Grissino-Mayer HD. 2009. Climate-tree growth relationships of longleaf pine (*Pinus palustris* Mill.) in the Southeastern Coastal Plain, USA. Dendrochronologia 27:31-43.

Holmes RL, Cook ER. 1986. Guide for computer program ARSTAN [Internet]. Tucson (AZ): Laboratory of Tree-ring Research, University of Arizona. [cited 2011 Feb 4]. Available from: http://www.ltrr.arizona.edu/pub.

Hopton HM, Pederson N. 2005. Climate sensitivity of Atlantic white cedar at its northern range limit. In: Burke MK, Sheridan P, editors. Atlantic white cedar ecology, restoration, and management: proceedings of the Arlington Echo symposium. 2003 Jun 2-4; Millersville, MD. Asheville (NC): US Forest Service Southern Research Station. p. 22-30. General Technical Report SRS-91.

Kearney TH. 1901. Report on a botanical survey of the Dismal Swamp region. Washington (DC): US Department of Agriculture. Contributions from the US National Herbarium 5(6):321-550.

Korstian CF. 1924. Natural regeneration of southern white cedar. Ecology. 5(2):188-191.

Korstian CF, Brush WD. 1931. Southern white cedar. Washington (DC): US Department of Agriculture. Technical Bulletin No. 251.

References

Kozlowski TT. 1979. Tree growth and environmental stresses. Seattle (WA): University of Washington Press.

Kozlowski TT, Pallardy SG. 1997. Physiology of woody plants. 2nd ed. San Diego (CA): Academic Press.

Laderman AD. 1989. The ecology of Atlantic white cedar wetlands: a community profile. Washington (DC): US Fish and Wildlife Service. Biological Report 85(7.21).

Levy GF, Walker SW. 1979. Forest dynamics in the Dismal Swamp of Virginia. In: Kirk PW Jr, editor. The Great Dismal Swamp. Charlottesville (VA): University Press of Virginia. p. 101-126.

Levy GF. 1987. Atlantic white cedar in the Great Dismal Swamp and the Carolinas. In: Laderman AD, editor. Atlantic white cedar wetlands. Boulder (CO): Westview Press. p. 57-67.

Levy GF. 1991. The vegetation of the Great Dismal Swamp: a review and an overview. Virginia Journal of Science. 42(4):411-417.

Lichtler WF, Walker PN. 1979. Hydrology of the Dismal Swamp, Virginia-North Carolina. In: Kirk PW Jr, editor. The Great Dismal Swamp. Charlottesville (VA): University Press of Virginia. p. 140-168.

Lowie C, Belcher RT, Poovey B. 2009. Challenges and success of Atlantic white-cedar restoration at the Great Dismal Swamp National Wildlife Refuge. On-line proceedings of the 2009 Atlantic-white cedar symposium: the ecology and management of Atlantic white-cedar (*Chamaecyparis thyoides*) ecosystems [Internet]. 2009 Jun 9-11; Greenville, NC. [cited 2011 Oct 28]. Available from: http://www.ces.ncsu.edu/nreos/forest/feop/AWC2009/proceedings.

References

Luxmoore RJ, Oren R, Sheriff DW, Thomas RB. 1995. Source-sink-storage relationships of conifers. In: Smith WK, Hinckley TM, editors. Resource physiology of conifers: acquisition, allocation, and utilization. San Diego (CA): Academic Press. p. 179-216.

MacDonald SE, Yin F. 1999. Factors influencing size inequality in peatland black spruce and tamarack: evidence from post-drainage release growth. Journal of Ecology. 87(3):404-412.

Megonigal JP, Conner WH, Kroeger S, Sharitz RR. 1997. Aboveground production in southeastern floodplain forests: a test of the subsidy-stress hypothesis. Ecology. 78(2):370-384.

Meldahl RS, Pederson N, Kush JS, Varner JM III. 1999. Dendrochronological investigations of climate and competitive effects on longleaf pine growth. In: Wimmer R, Vetter RE, editors. Tree ring analysis: biological, methodological, and environmental aspects. Wallingford (GB): CABI Publishing. p. 265-285.

Merry SD. 2005. Factors affecting tree ring width in Atlantic white cedar, *Chamaecyparis thyoides* (L.) B.S.P., within Great Dismal Swamp National Wildlife Refuge and Alligator River National Wildlife Refuge [master's thesis]. Newport News (VA): Christopher Newport University.

Mitsch WJ, Rust WG. 1984. Tree growth responses to flooding in a bottomland forest in northeastern Illinois. Forest Science. 30(2):499-510.

National Climatic Data Center. 2010. Online climate data directory [Internet]. Ashville (NC): National Climatic Data Center. [cited 2010 Jul 14]. Available from: http://www.ncdc.noaa.gov/oa/climate/climatedata.html.

References

NOAA Paleoclimatology Program. 2008. User guide to COFECHA output files [Internet]. Boulder (CO): NOAA Paleoclimatology Program. [cited 2011 Feb 2]. Available from: http://www.ncdc.noaa.gov/paleo/treering/cofecha/userguide.html.

Oren R, Sheriff DW. 1995. Water and nutrient acquisition by roots and canopies. In: Smith WK, Hinckley TM, editors. Resource physiology of conifers: acquisition, allocation, and utilization. San Diego (CA): Academic Press. p. 39-74.

Pallardy SG, Cermak J, Ewers FW, Kaufmann MR, Parker WC, Sperry JS. 1995. Water transport dynamics in trees and stands. In: Smith WK, Hinckley TM, editors. Resource physiology of conifers: acquisition, allocation, and utilization. San Diego (CA): Academic Press. p. 301-389.

Palmer WC. 1965. Meteorological drought. Washington (DC): US Weather Bureau. Research Paper No. 45.

Pederson N, Cook ER, Jacoby GC, Peteet DM, Griffin KL. 2004. The influence of winter temperatures on the annual radial growth of six northern range margin tree species. Dendrochronologia. 22:7-29.

Phillips RW, Hughes JH, Buford MA, Gardner WE, White FM, Williams CG. 1998. Atlantic white cedar in North Carolina, USA. In: Laderman AD, editor. Coastally restricted forests. New York (NY): Oxford University Press. p. 156-170.

Phipps RL. 1970. The potential use of tree rings in hydrologic investigations in eastern North America with some botanical considerations. Water Resources Research. 6(6):1634-1640.

Phipps RL, Ireley DL, Baker CP. 1979. Tree rings as indicators of hydrologic change in the Great Dismal Swamp, Virginia and North Carolina. Reston (VA): US Geological Survey. Water Resources Investigations Report 78-136.

References

Phipps RL. 1982. Comments on interpretation of climatic information from tree rings, eastern North America. Tree-ring Bulletin. 42:11-22.

Phipps RL. 1985. Collecting, preparing, crossdating, and measuring tree increment cores. Reston (VA): US Geological Survey. Water Resources Investigations Report 85-4148.

Pinchot G, Ashe WW. 1897. Timber trees and forests of North Carolina. Raleigh (NC): North Carolina Geological Survey. Bulletin No. 6.

Poovey B. 2010. Forester. US Fish and Wildlife Service, Great Dismal Swamp National Wildlife Refuge, Suffolk, VA.

Powell SW, Day FP Jr. 1991. Root production in four communities in the Great Dismal Swamp. American Journal of Botany. 78(2):288-297.

Prescott CE. 2005. Decomposition and mineralization of nutrients from litter and humus. In: BassiriRad H, editor. Nutrient acquisition by plants: an ecological perspective. Berlin (DE): Springer-Verlag. p. 15-41.

Robertson PA. 1992. Factors affecting tree growth on three lowland sites in southern Illinois. American Midland Naturalist. 128(2):218-236.

Rodgers HL, Day FP, Atkinson RB. 2003. Fine root dynamics in two Atlantic white-cedar wetlands with contrasting hydroperiods. Wetlands. 23(4):941-949.

References

Russell JH. 1998. Genecology of *Chamaecyparis nootkatensis*. In: Laderman AD, editor. Coastally restricted forests. New York (NY): Oxford University Press. p. 82-92.

Seim AM. 2005. The effect of climate on the growth of red maple (*Acer rubrum* L.) and Atlantic white cedar (*Chamaecyparis thyoides* (L.) B.S.P.) in the Great Dismal Swamp National Wildlife Refuge [master's thesis]. Newport News (VA): Christopher Newport University.

Shaler NS. 1890. General account of the fresh-water morasses of the United States with a description of the Dismal Swamp District of Virginia and North Carolina. Washington (DC): US Geological Survey. p. 255-339. Annual Report 10.

Sprugel DG, Ryan MG, Brooks JR, Vogt KA, Martin TA. 1995. Respiration from the organ level to the stand. In: Smith WK, Hinckley TM, editors. Resource physiology of conifers: acquisition, allocation, and utilization. San Diego (CA): Academic Press. p. 255-299.

Stahle DW, Cleaveland MK, Hehr JG. 1988. North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985. Science. 240(4858):1517-1519.

Stewart PC. 1979. Man and the swamp: the historical dimension. In: Kirk PW Jr, editor. The Great Dismal Swamp. Charlottesville (VA): University Press of Virginia. p. 57-73.

Stewart PC. 1981. The shingle and lumber industries in the Great Dismal. Journal of Forest History. 25:98-107.

Stockton CW. 1990. Climatic, hydrologic and water supply inferences from tree rings. Civil Engineering Practice. 37-52.

References

SYSTAT. 2009. SYSTAT 13 statistics manual I II III IV. Chicago (IL): SYSTAT Software Inc.

Teskey RO, Bongarten BC, Cregg BM, Dougherty PM, Hennessey TC. 1987. Physiology and genetics of tree growth response to moisture and temperature stress: an examination of the characteristics of loblolly pine (*Pinus taeda* L.). Tree Physiology. 3:41-61.

US Army Corps of Engineers. 2007. Dismal Swamp Canal navigation project: Lake Drummond daily water-level readings. Norfolk (VA) District: US Army Corps of Engineers.

US Fish and Wildlife Service. 2004. Environmental assessment for the Atlantic white cedar salvage and restoration at the Great Dismal Swamp National Wildlife Refuge. Suffolk (VA): Great Dismal Swamp National Wildlife Refuge.

US Fish and Wildlife Service. 2006. Great Dismal Swamp National Wildlife Refuge and Nansemond National Wildlife Refuge final comprehensive conservation plan. Suffolk (VA): Great Dismal Swamp National Wildlife Refuge.

US Fish and Wildlife Service. 2010a. South One Wildfire, 2008 [Internet]. Hadley (MA): USFWS Northeast Fire Program. [cited 2010 Sep 29]. Available from: http://www.fws.gov/northeast/refuges/fire/wildfire.html.

US Fish and Wildlife Service. 2010b. Great Dismal Swamp National Wildlife Refuge plants Atlantic white cedars in wake of South One Fire [Internet]. Hadley (MA): USFWS Northeast Fire Program. [cited 2010 Sep 29]. Available from: http://www.fws.gov/northeast/refuges/fire/South%20One%20rehab.html.

References

US Fish and Wildlife Service. 2011. Great Dismal Swamp National Wildlife Refuge website [Internet]. Hadley (MA): USFWS Northeast Regional Office. [cited 2011 Oct 29]. Available from: http://www.fws.gov/northeast/greatdismalswamp.

US Geological Survey. 1982. Aerial photo 0137. Earth explorer website [Internet]. Sioux Falls (SD): USGS Earth Resources Observation and Science Center. [cited 2010 Aug 7]. Available from: http://edcsns17.cr.usgs.gov/earthexplorer.

Walbridge MR. 1991. Phosphorus availability in acid organic soils of the lower North Carolina Coastal Plain. Ecology. 72(6):2083-2100.

Wigley TML, Briffa KR, Jones PD. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. Journal of Climate and Applied Meteorology. 23:201-213.

Yamaguchi DK. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research. 21:414-416.

Zar JH. 1999. Biostatistical analysis. 4th ed. Upper Saddle River (NJ): Prentice Hall.

Questions

Atlantic White Cedar stand in Great Dismal Swamp (Pre-Isabel)

Feasibility

- Effective tree-ring studies require species that are climate sensitive and sites in which environmental conditions vary annually
- Sequences of wide and narrow rings are often indicative of climate sensitivity and annual variation of growth conditions
- Closed-canopy, forested sites where ground water influence is strong and climate is warm and humid may produce little ring-width variation

Carbon storage

- Most early-season (earlywood) growth that occurs in the lower stem is dependent on carbon stored from the previous year, as carbohydrates produced in the spring primarily support crown and upper-stem growth
- Dry conditions in summer or early autumn can slow aboveground growth, limit demand for carbohydrates, and initiate net carbon storage earlier than normal
- Reduced aboveground growth and carbon demand results in an increase in carbon reserves available to support radial growth in the following year
- Conversely, extended favorable conditions in summer and early autumn can prolong aboveground growth and increase demand for stored carbon, resulting in less carbon availability in the following spring

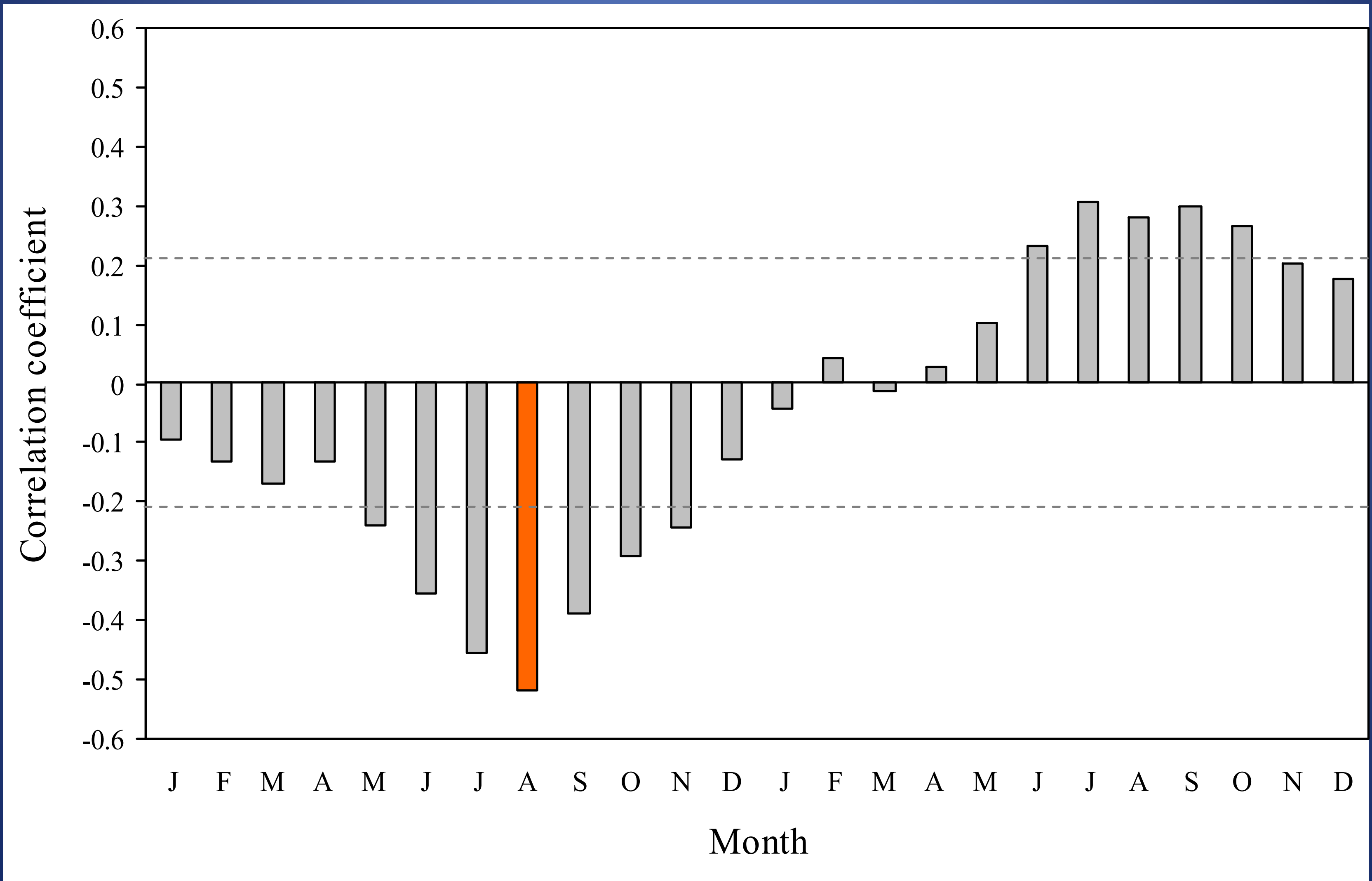
Shoot growth

- Differences in shoot growth during dry and wet years can also influence carbon storage
- During dry periods, conifers tend to shed leaves in order to reduce respiration costs and preserve stored carbon
- Peaks in litterfall corresponding with dry periods have been observed in AWC stands in GDSNWR
- Conversely, crown expansion during a favorable summer and autumn may subject trees to increased transpiration and respiration costs in the following year if conditions are unfavorable, limiting radial growth

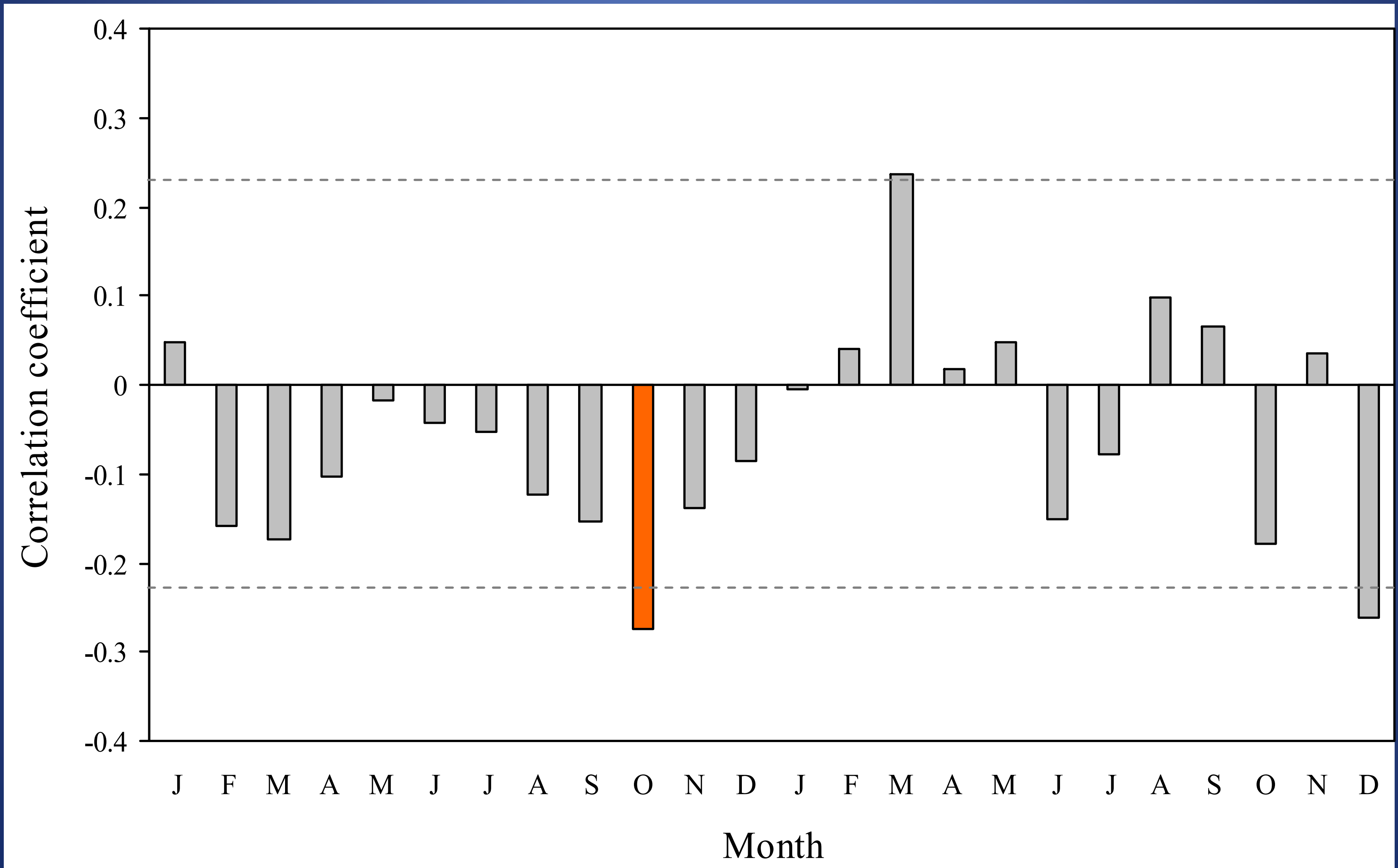
Nutrient dynamics

- All available accounts from AWC stands in GDSNWR suggest that decay of soil organic matter in the root-zone is not limited by dry conditions
- However, during dry periods, most mineralized nutrients are immobilized by microorganisms, limiting nutrient release and plant uptake
- In the absence of precipitation, immobilized nutrients may not be returned to soil solution until the microbial biomass dies and decays in winter
- Turnover of fine roots and increased leaf fall during dry conditions, plus turnover of microbial biomass and return of the water table to the root zone in winter, may result in a relatively high soil nutrient pool in following spring

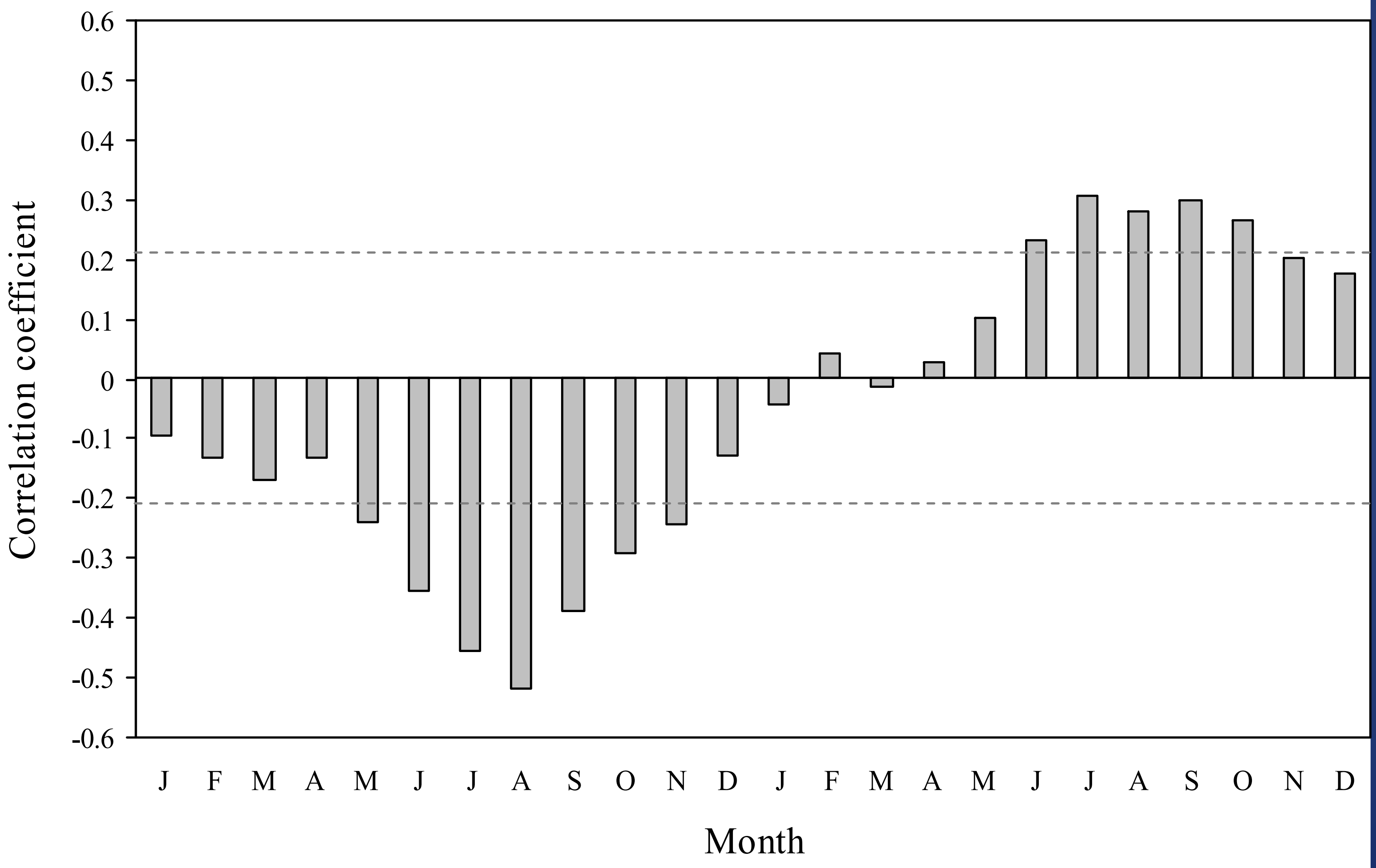
Previous-year August PDSI



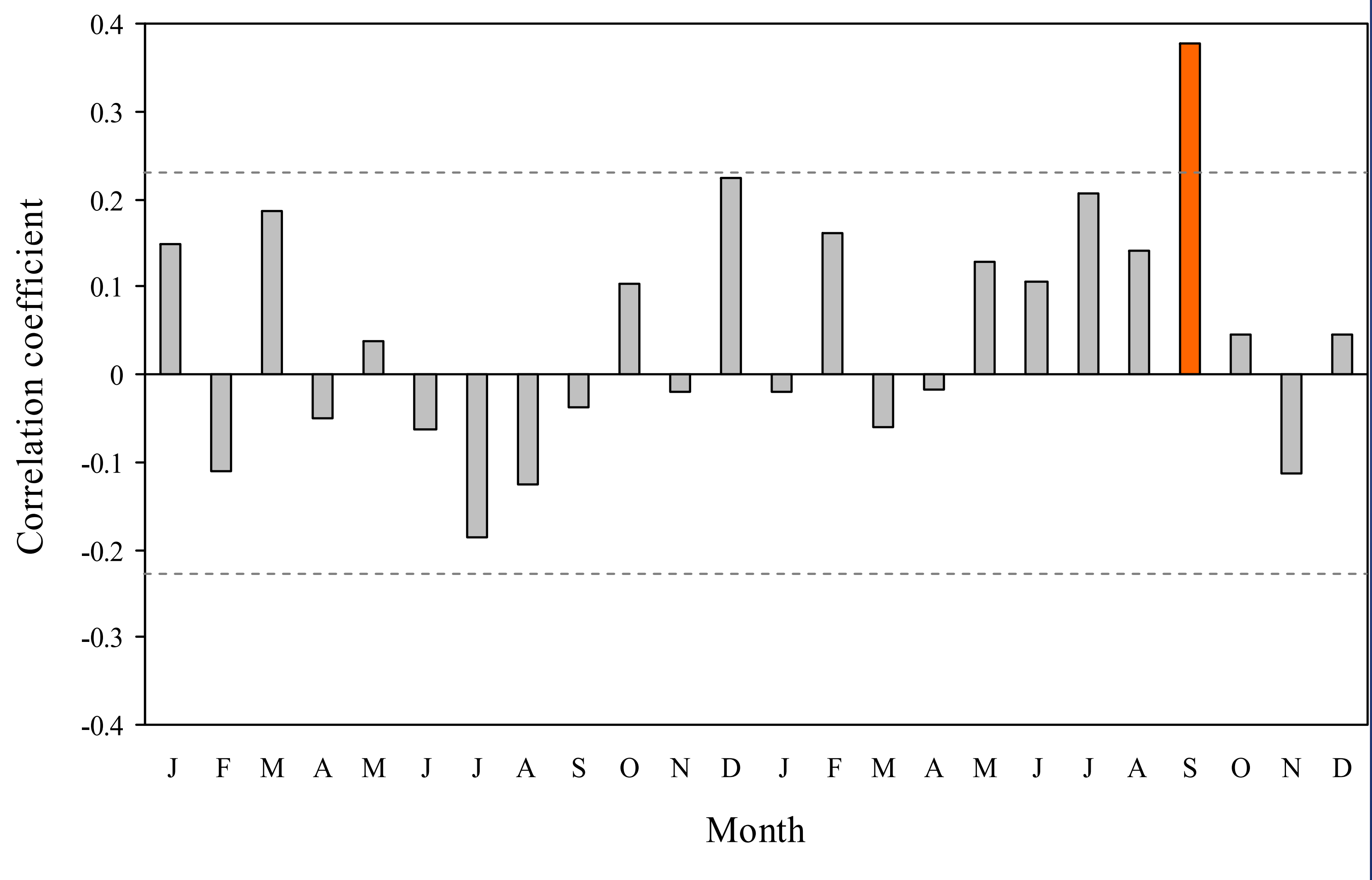
Previous-year October temperature



Current-year summer PDSI



Current-year September rainfall



AWC radial growth in GDSNWR

- Biweekly diameter growth measurements of AWC by Day (1985) indicated that most growth occurred from mid-April through June
- This result is probably typical of most years because soil moisture content appears most favorable for growth in spring and early summer
- However, radial growth is indeterminate and is very responsive to soil moisture availability throughout the growing season
- Delay or absence of summer drawdown results in an extended period of earlywood growth and thus a wide annual ring
- Development and persistence of dry conditions through summer and autumn slows earlywood growth and may initiate latewood formation, resulting in a narrow ring

Significant correlations

- A significant correlation suggests that a climatic factor or related site factor varied sufficiently during a given month throughout much of the study period to reduce or enhance radial growth
- Most important climatic variables: previous-year August PDSI, previous-year October temperature, and current-year September rainfall
- Associated with root-zone soil moisture availability in late summer and early autumn
- This suggests that soil moisture in spring was relatively consistent and conducive to AWC radial growth in GDSNWR, while soil moisture in summer and autumn was variable and potentially limiting during much of the study period

Previous-year October temperature

- Consecutive negative correlations with temperature often coincide with periods of water stress

- The trend of negative correlations observed here corresponded with the annual drawdown of the water table through late summer and autumn in GDSNWR and peaked in October when water table was likely at its lowest elevation in most years

- During a dry autumn, cool temperatures are especially helpful in limiting respiration costs and preserving stored carbon

- Conversely, warm temperatures and favorable soil moisture supply in October appear very conducive to facilitating nutrient release and uptake, prolonging aboveground growth, and reducing carbon reserves

Previous-year summer and autumn soil moisture

- Negative correlations between ring width and previous-year July, August, and September PDSI were the strongest observed in this study

- Most influential climate-related factor on AWC ring width in GDSNWR

- Five of the top 6 high-growth years of AWC in GDSNWR were preceded by a dry cycle with 12 or more consecutive months of mild to severe drought conditions

- The other top growth year occurred during a drought but was preceded by the driest year of the study period

Comparison with other studies - general

- Strong influence of previous-year climatic conditions is not surprising:

  Previous-year climatic conditions have a strong effect on ring-width variation of conifers in semiarid, cold-temperate, and boreal regions

- However, the sign / direction of the response to previous-year climate observed in this study appears to be uncommon

  Conifers of the above-referenced settings often exhibit positive correlations between ring width and unfavorable conditions in the previous year

  In this study, unfavorable climatic conditions in the previous year were dominant factors in producing wide rings in the following year

Comparison with other studies - Southeast

- Significant, negative correlations between ring width and previous-year summer or autumn PDSI were reported for:

  Longleaf pine in Alabama, South Carolina, Texas, and Virginia

  Eastern red cedar in Virginia

- Significant, negative correlations between ring width and previous-year summer or autumn rainfall were reported for:

  Loblolly pine and red maple in GDSNWR

- Like AWC, all of these species do not exhibit determinate shoot growth

Comparison with other studies - AWC

- This was only the fourth study that analyzed the effect of previous-year soil moisture on AWC radial growth (and the first to use PDSI)

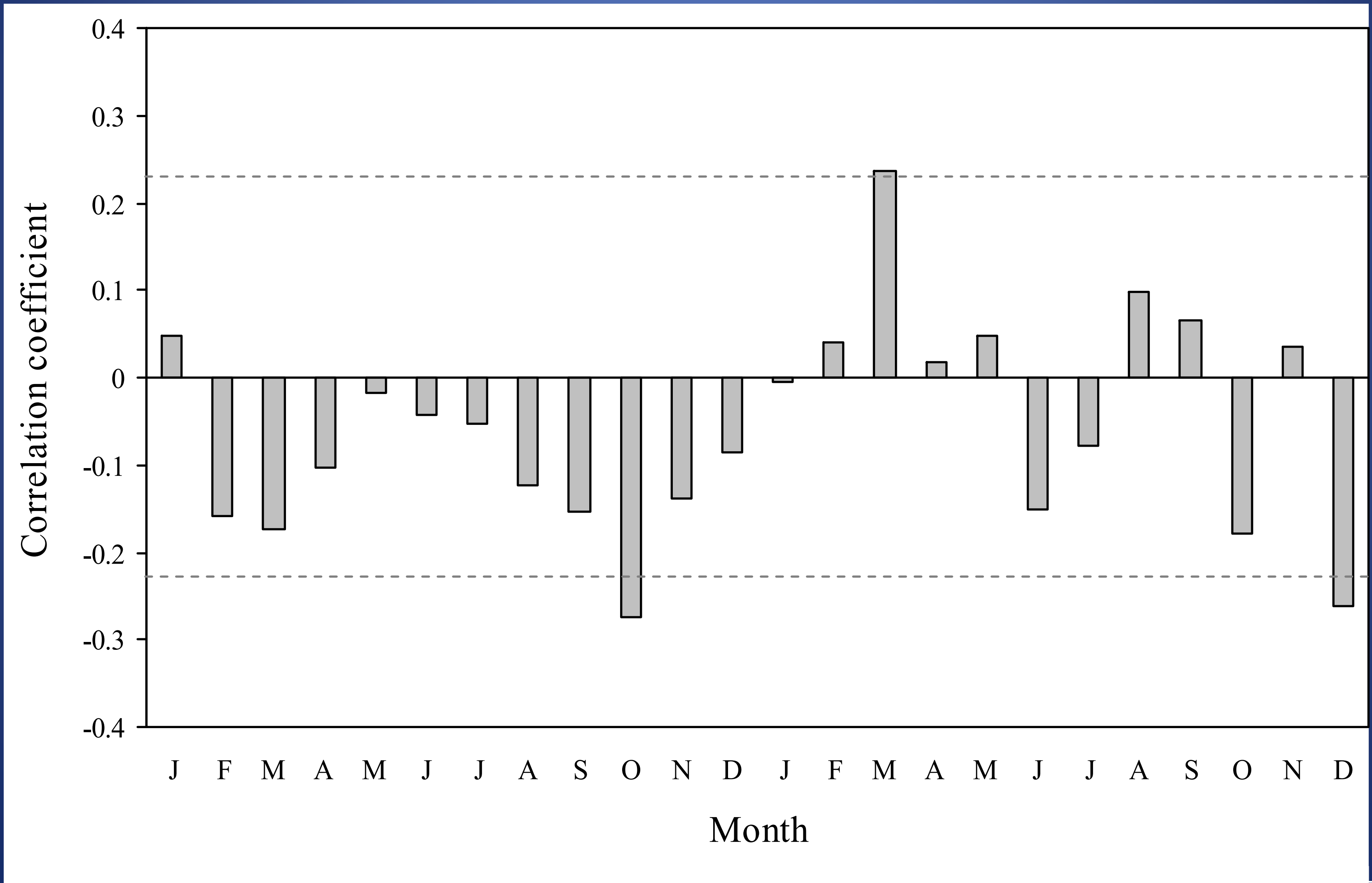
  AWC in Rhode Island using hydrologic variables (Golet and Lowry 1987)

  AWC in GDSNWR and ARNWR using rainfall (Merry 2005; Seim 2005)

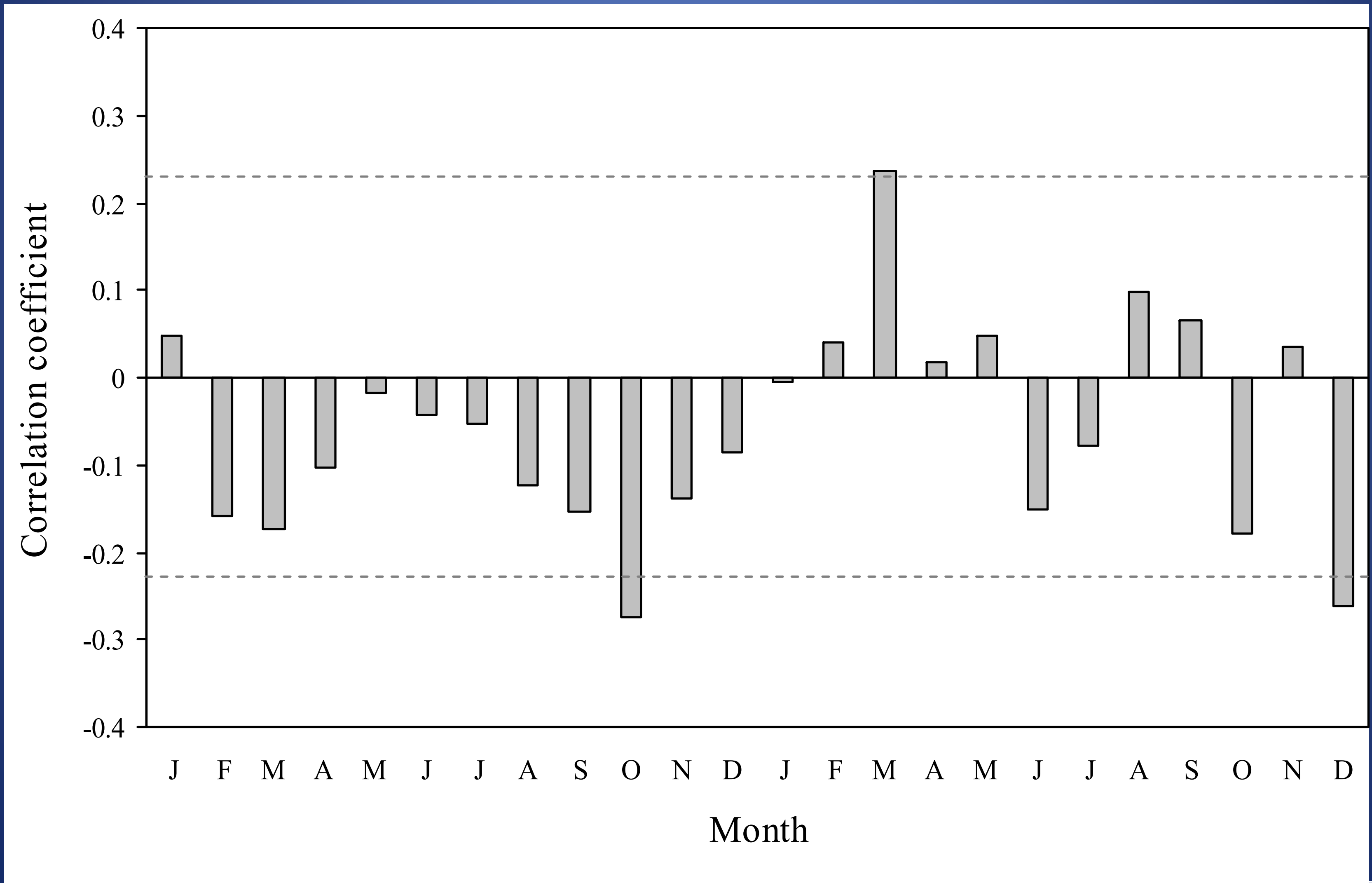
- The strongest similarity between this study and those by Merry and Seim was the negative correlation between ring width and previous-year late-summer soil moisture / rainfall

- Consistent with the negative relationship between radial growth and previous-year summer water table elevation reported in Rhode Island

Correlations between RESID and mean temperature



Correlations between RESID and mean temperature



Same site in GDS, timber harvested

ARNWR precipitation and temperature correlations (Merry 2005)