

# Understanding the Physical and Biological Drivers of Observed Evapotranspiration Declines in the Northern Forest Region

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*Long-term trends in ET vary across seven research watersheds in the northeast. Only the longest records show declines (about 10%), but tree-ring isotopes indicate large increases in water-use efficiency at all sites since 1950.*

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<http://www.nsrcforest.org>

# Collaborators

*This work would not have been possible without many decades of careful work measuring water budgets at the various research sites. We thank our collaborators for their expertise about each site and for access to each site's long-term data.*

- Bear Brook: Ivan Fernandez and Sarah Nelson; University of Maine
- Biscuit Brook: Doug Burns; USGS
- Fernow Experimental Forest: Mary Beth Adams and Tom Schuler; USFS
- Huntington Forest: Myron Mitchell, Pat McHale, Colin Beier, and Dan Bishop; SUNY-ESF
- Leading Ridge: Beth Boyer; Penn State
- Sleepers River: Jamie Shanley and Ann Chalmers; USGS

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# Project Summary

**Rationale:** Evapotranspiration (ET) is a major component of terrestrial water and energy budgets, and as such, changes in the rate or temporal or spatial dynamics of ET can have important consequences for the reliability of surface freshwater resources, ecosystem productivity, and soil biogeochemical processes, as well as feedbacks to the global climate system. A general consensus has emerged that the warming climate is likely to lead to an overall intensification of the global hydrological cycle. However, the consequences of multiple global change drivers on terrestrial evapotranspiration remain unclear at the regional scale.

**Methods:** We examined long-term trends and interannual variation in evapotranspiration, calculated by mass balance, in seven unmanaged forested watersheds from Maine to West Virginia. We looked at the relationship between this basin-scale water balance and annual climate metrics. We also sampled tree rings from each site and examined correlations of ET and climate with growth and isotopic metrics of water use.

**Findings:** Two of the three watersheds with records longer than 50 years show significant ET declines of ~2% per decade. We did not detect significant trends in the shorter records at the

other four watersheds.

In the more southern watersheds, there were clear correlations between growth, water use efficiency, ET, and growing season precipitation. In the more northern sites, there were fewer consistent relationships among climate, ET, and tree physiology. Across all sites, there were clear increases in water use efficiency since 1950.

**Implications:** Better understanding the trends in transpiration and water-use efficiency has important implications for understanding growing season streamflow, soil moisture, and the vulnerability of forest ecosystems to drought conditions. We see little evidence for increases in ET in the humid northeast; instead modest declines are seen where the data allow us to detect them. This likely relates to increases in water use efficiency due to atmospheric C enrichment, which may offset the effect of warming on ET. Our correlation results demonstrate much greater sensitivity of tree growth and physiology to drought in the southern part of our study region than in the more northern part, which may respond more subtly to a wider array of variables including the timing of seasonal transitions, growing season temperature, humidity, and cloudiness.

# Background and Justification

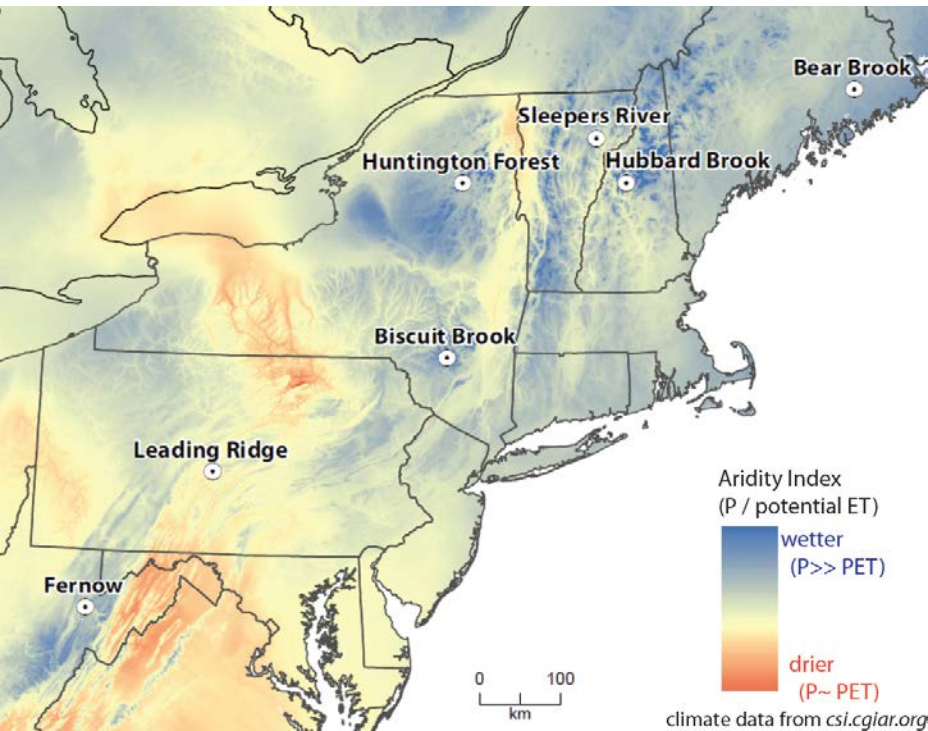
Evapotranspiration (ET) is the process by which water is moved from the soil to the atmosphere via movement through plants. Forests use approximately half of the precipitation received annually in the northeast, and the rate of ET is controlled by physical factors (temperature, humidity, sunlight, windiness) as well as trees' physiological control of their stomata (gas-exchange pores on their leaves).

Most previous theories to explain changes in ET have centered on physical controls. For example, reduced solar radiation associated with increases in atmospheric aerosols have been one explanation for ET declines (Alpert and Kishcha 2008). Others suggest that increases in precipitation and associated cloud cover have caused declines in ET (Hobbins et al. 2004). World-wide increases in runoff have been attributed to declining ET resulting from reduced vegetation water use due to drought (Gardelle et al. 2010) or increasing atmospheric CO<sub>2</sub> (Gedney et al. 2006).

The influence of vegetation on ET through plant water uptake from the soil is directly related to the ability of plants to regulate the relationship between photosynthesis (carbon coming into the leaf) and transpiration (water leaving the leaf) in response to changing physiological and environmental conditions. This ratio between CO<sub>2</sub> uptake and water loss can be directly quantified at the leaf scale as water use efficiency (WUE; Nobel 2005). Changes in WUE in response to climate variability are particularly useful measures of the interaction between the water cycle and plant growth (Chen and Coughenour 2004). The stable carbon isotope ratio ( $\delta^{13}\text{C}$ ) of plant tissue provides a robust measure of the time-integrated intrinsic water use efficiency (WUE, Dawson et al. 2002). When paired with oxygen isotope ratios ( $\delta^{18}\text{O}$ ), additional inference can be made about whether changes in WUE were due to changing rates of carbon fixation or changes in stomatal closure.

Rising atmospheric CO<sub>2</sub> may directly affect plant physiological controls over water fluxes by increasing photosynthesis or reducing transpiration. Such a 'fertilization effect' on WUE has been documented in several studies, but may not translate to increased growth where water is not normally limiting, and may simply reduce overall water use. We are not aware of any previous work that explicitly links carbon isotope changes in vegetation with long-term ET dynamics.

# Methods: study sites

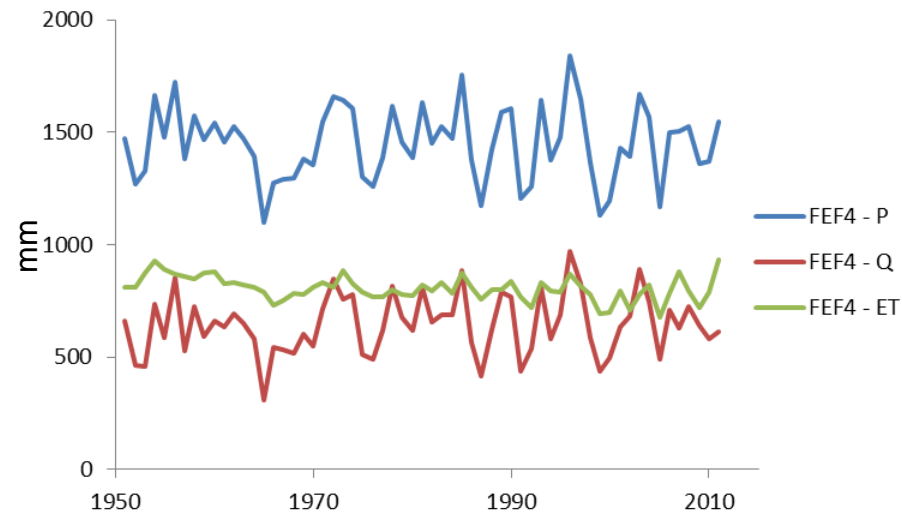


We worked at seven unmanaged, forested small watersheds in the northeast. All sites have precipitation and streamflow records ranging from 18-63 years.

At each site, we examined water balance (below) and tree-ring metrics of water use efficiency and evapotranspiration (ET). The optimal water year was selected for analysis at each site. Cleaned and organized data were shared with site collaborators. Trends were evaluated using Kendall's  $\tau$ .

Water balance (precipitation, streamflow, and ET calculated by difference for each water year) over up to 6 decades.

These data are from Fernow Experimental Forest and show a significant 10% decline in ET from 1951 to 2011.





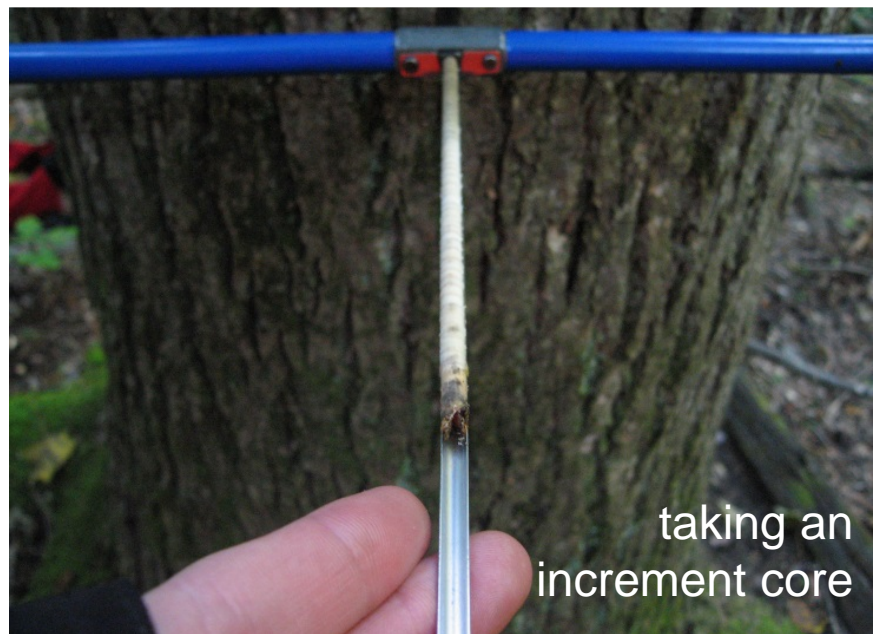
# Methods: tree rings

We sampled tree rings from the 2 or 3 most dominant canopy species of trees at each study site.

An increment borer was used to take 2 or 3 cores from 10-20 trees per species per site. Ring widths were measured and each growth time-series was validated before cutting annual rings and extracting the cellulose for isotopic analysis.

The ratio of stable carbon isotopes in a plant serves as a metric of water use efficiency (the ratio of carbon gained per unit water transpired, a physiological determinant of water use). This isotope ratio is preserved in the wood formed each year.

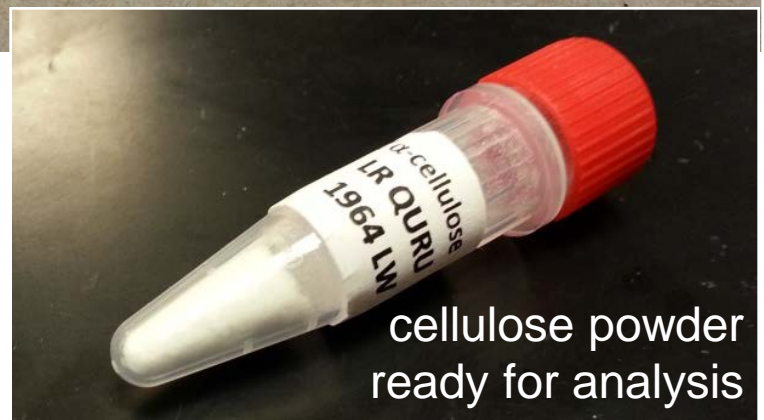
The ratio of stable oxygen isotopes serves as a metric of the atmospheric water demand (a physical determinant of water use).



taking an increment core



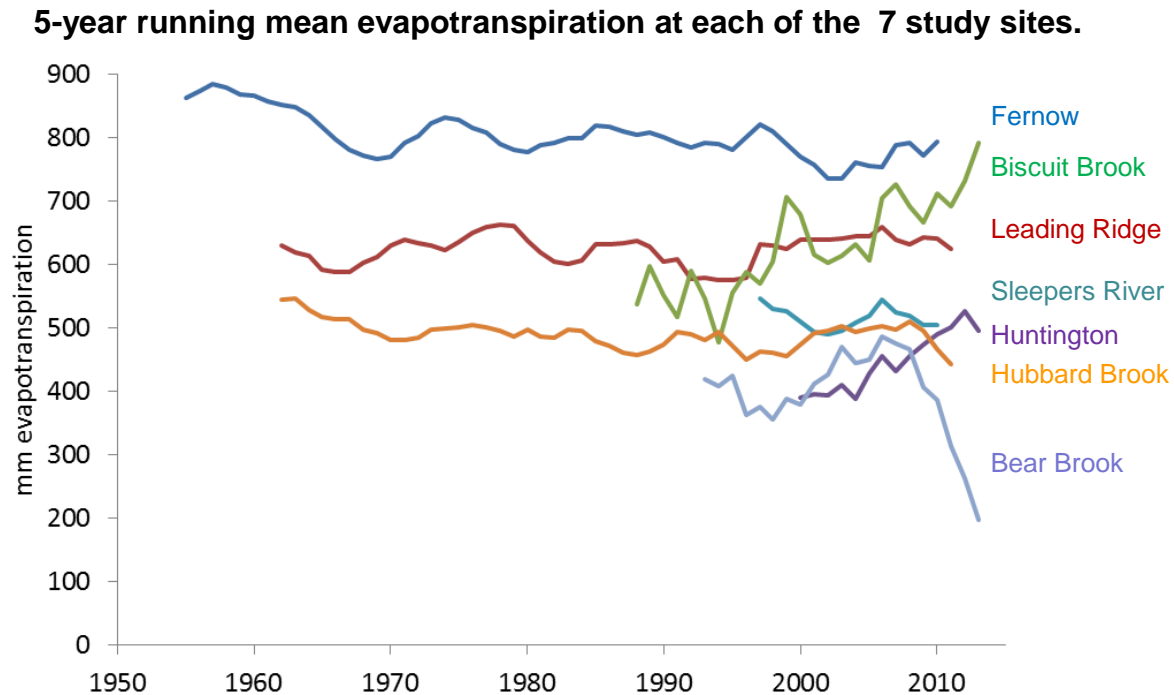
cutting the growth rings



cellulose powder ready for analysis

# Results: Water balance trends and variation

- Precipitation has generally increased (data not shown).
- ET declined ~10% in 2 of the 3 longest records (Fernow & Hubbard Brook).
- Recent departures in ET at Biscuit Brook, Bear Brook are questionable (large recent outlier years).
- Variation in ET correlates with precipitation at the three more southern sites.
- ET variation at the northern sites shows little consistent pattern, but may relate in part to summer temperature.
- The negative relationship with summer precipitation at Hubbard Brook may mean that humidity or cloudiness (which correlate with precip.) is the largest control on ET there.



**Correlations (R values) of ET with various climate metrics. Significant correlations shown in bold.**

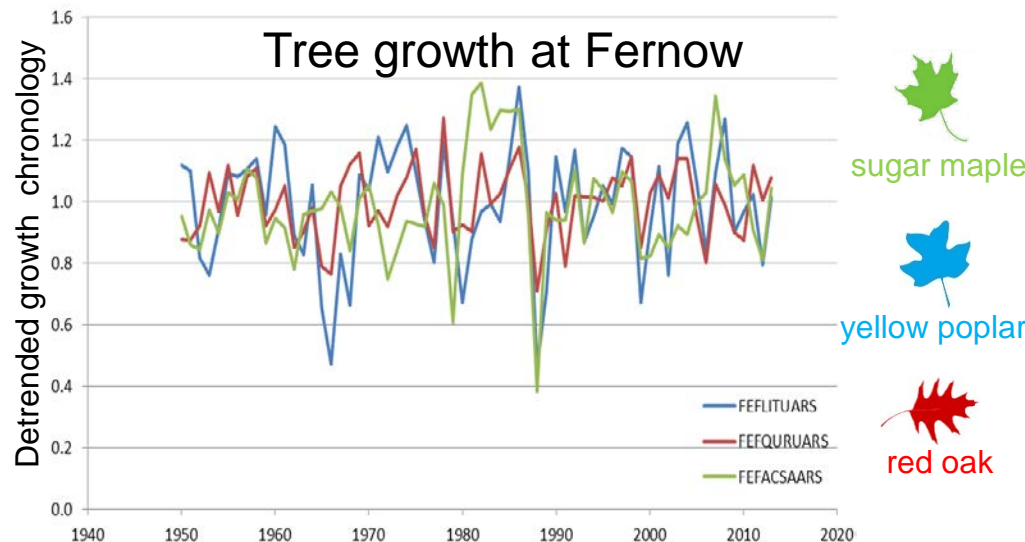
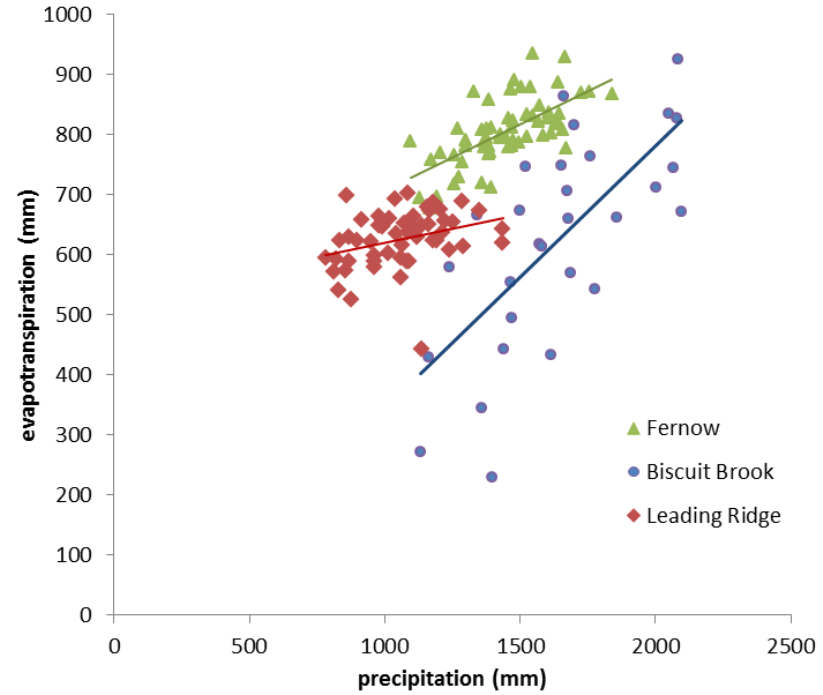
Site (#yrs)	Tmax JJA	Tmin JJA	VPD JJA	P WY	P JJA	PDSI JJA	PET WY	PET JJA
Bear Br. (25)	<b>0.41</b>	0.11	NA	0.13	-0.14	-0.29	0.13	0.26
Hubbard Br. (54)	0.02	-0.02	0.11	-0.16	<b>-0.31</b>	-0.20	-0.19	0.00
Sleepers R. (18)	0.02	0.06	NA	0.15	0.44	0.08	-0.21	-0.15
Archer Cr. (18)	0.40	0.48	NA	0.20	0.29	0.07	0.32	0.27
Biscuit Br. (29)	0.02	-0.02	NA	<b>0.70</b>	<b>0.37</b>	0.19	-0.13	0.01
Leading Ridge (52)	-0.21	0.01	-0.27	<b>0.32</b>	<b>0.45</b>	0.09	0.12	-0.13
Fernow (61)	0.12	-0.12	-0.09	<b>0.66</b>	<b>0.39</b>	0.13	0.15	0.19

T = temperature. P = precipitation. VPD = vapor pressure deficit (higher values are drier air); values are for the nearest airport. PDSI = Palmer Drought severity index (higher values are wetter years). PET = potential evapotranspiration (CRU TS3.1 dataset). JJA = June, July, and August. WY = water year.



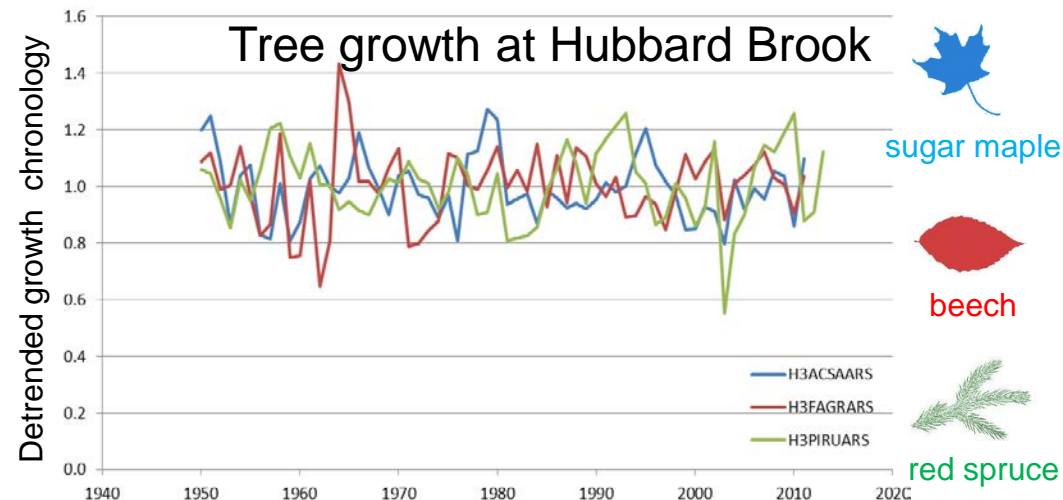
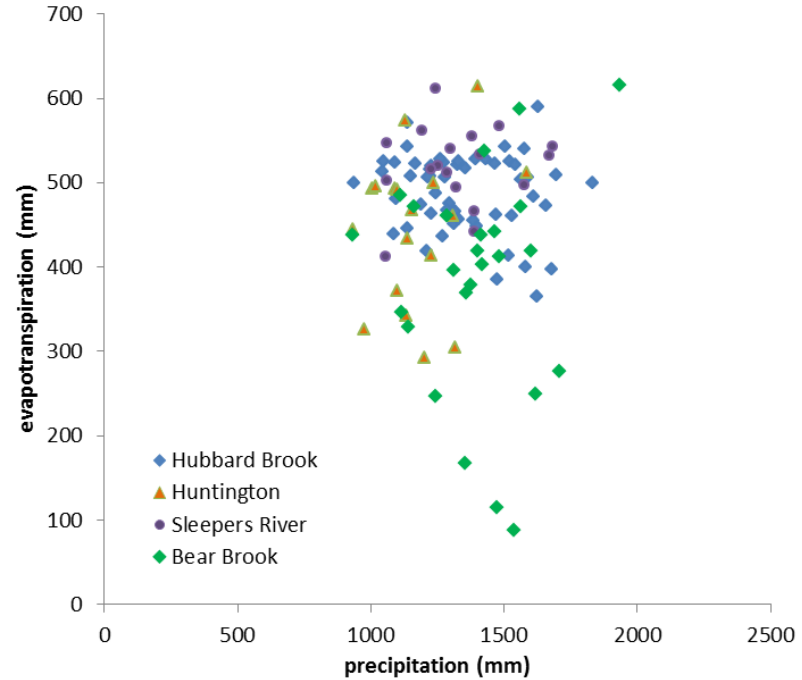
# Results: Growth and Physiology (southern sites)

- At Fernow, Leading Ridge, and Biscuit Brook, ET showed clear correlations with precipitation, indicating at least transient water limitation of transpiration in dry years.
- Tree growth (detrended ARS time series for Fernow shown here) also correlated with precipitation, indicating consequences of drought years for ecosystem production and carbon balance.
- Carbon isotope ratios indicate that water use efficiency increased in dry years, as stomata closed to conserve water.

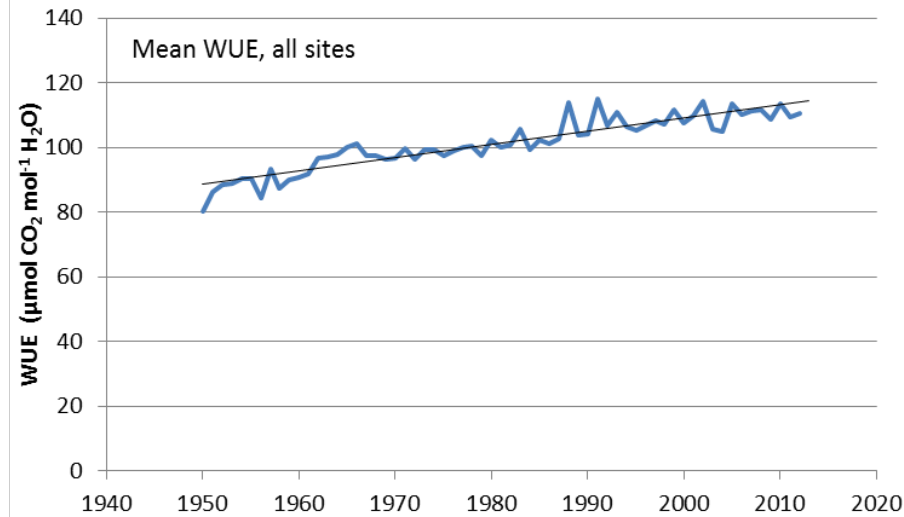


# Results: Growth and Physiology (northern sites)

- At Hubbard Brook, Bear Brook, Sleepers River, and Huntington, ET did not correlate with annual or growing season precipitation, showing that water limitation of ET is infrequent.
- Tree growth (detrended ARS time series for Hubbard Brook shown here) also showed little relationship with precipitation, indicating that water availability also rarely limits growth.
- Carbon isotope ratios indicate that stomatal regulation did not respond strongly to water availability or other climate variables examined.

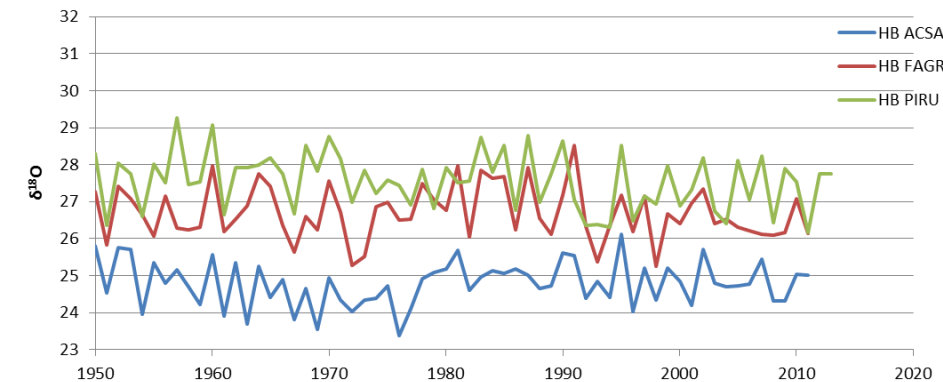


# Results: Trends in Water-use Efficiency



- Water-use efficiency time series showed significant linear increases across all species examined at all seven sites. This fits the global pattern, as a consequence of greater C concentrations in the atmosphere.
- There were no long-term trends in oxygen isotope ratios, supporting the hypothesis that increases in WUE were due to stomatal closure in a more carbon-rich atmosphere, but indicating little change in overall atmospheric water demand.
- For some isotope chronologies, there were significant but weak correlations between  $\Delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , possibly indicating water stress induced by high VPD. Most of these relationships were driven by just a few hot, dry years.

## Oxygen isotopes at Hubbard Brook



# Implications

- Better understanding the trends in transpiration and water-use efficiency has important implications for understanding growing season streamflow, soil moisture, and the vulnerability of forest ecosystems to drought conditions.
- The previously documented decline in ET at Hubbard Brook (Campbell et al. 2011, Hamburg et al. 2013) is also seen at Fernow, but not region-wide, though it may just be difficult to detect in shorter records. This implies that ecosystem responses to a changing climate and atmosphere are likely to be site-specific and not uniform across the region.
- We see little evidence for widespread, regionally consistent changes in ET in the humid northeast. This is similar to the findings of Huntington and Billmire (2014), despite clear directional climate changes including warming and increases in precipitation.

- The sensitivity of ET, growth, and water use efficiency to precipitation at the three more southern sites indicates that some degree of water limitation does occur in central Appalachian forests, and that forests reduce their productivity in response to this stress. Over the past 6 decades, changes in temperature and humidity appear to play less of a role than variation in precipitation in influencing ET and tree physiology.
- There were few significant relationships seen between ET, climate, tree growth, and isotopic metrics of physiology in the four more northern sites. Even the severe regional drought of the 1960s (Cook et al. 1977, Seager et al. 2012) did not show up in many of the growth or isotope chronologies, indicating that water stress of the sort experienced further south is relatively unimportant, at least at the annual time scale. It may be that climate variables we could not account for are important, including the timing of seasonal transitions, humidity, and cloudiness.

# Future directions

- Future work examining the sensitivity of northeastern forests to water availability includes drought experiments currently being implemented at Hubbard Brook and in Durham, NH. The effects of a 50% reduction in precipitation on above- and below-ground production, leaf gas exchange, and other ecosystem parameters will be measured. These results will be compared with the tree ring results from past droughts in the same species, to better understand drought responses by species.
- We are also beginning to investigate whether differences in water yield among treated watersheds at Hubbard Brook (e.g. Green et al. 2013) can be seen in tree-ring isotopes relative to the control chronology we examined here.



*A plot in the NSRC-funded DroughtNet precipitation exclusion experiment at Hubbard Brook, underway in 2015.*



*A sugar maple core from Hubbard Brook watershed 1, showing increased growth after the 1999 fertilization with calcium silicate.*



# List of products

## Presentations

- Campbell JL, Green MB, Asbjornsen H, Vadeboncoeur MA. 2013. *Long-term changes in the water balance at the Hubbard Brook Experimental Forest: Is it emblematic of a regional climate-induced trend?* Invited talk at the Society of American Foresters National Convention, October 2013, Charleston, SC.
- Vadeboncoeur MA, Asbjornsen H, Green MB, Campbell JL. *Examining drivers of long-term trends in evapotranspiration in forested small catchments in the northeastern USA.* Talk presented at the American Society of Agricultural and Biological Engineers International Symposium on Evapotranspiration, April 2014, Raleigh, NC.
- Vadeboncoeur MA, Buzinski L, Asbjornsen H, Green MB. *Dendrochronological insights into growth and ecophysiology trends at Hubbard Brook.* Talk presented at the Hubbard Brook Cooperators' Meeting, July 2014.
- Vadeboncoeur MA, Asbjornsen H, Campbell J, Green MB. *Determining drivers of long-term trends in evapotranspiration in forested small catchments.* Poster presented at IUFRO World Congress, October 2014, Salt Lake City, UT.
- Campbell JL, Vadeboncoeur MA, Asbjornsen H, Green MB, Adams MB, Boyer EW. *Evaluating Biological and Physical Drivers of Evapotranspiration Trends at Northeastern US Watersheds.* Invited talk presented at Fifth Interagency Conference on Research in the Watersheds (ICRW5), March 2014, Charleston, SC.
- Vadeboncoeur MA, Asbjornsen H, Green MB, Campbell JL. *Examining long-term trends in evapotranspiration and water use efficiency in northeastern forested catchments.* Talk presented at 2015 NERC Conference, Saratoga Springs, NY.

## **Presentations (continued)**

Powers S, Vadeboncoeur MA, Asbjornsen H. *Growth rate of calcium-fertilized sugar maple and yellow birch at Hubbard Brook*. Poster presented at 2015 UNH Undergraduate Research Conference.

Vadeboncoeur MA, Asbjornsen H, Green MB, Campbell JL. *Drivers of trends and variation in tree-ring C and O isotopes at Watershed 3*. Talk to be presented at the Hubbard Brook Cooperators' Meeting, July 2015.

Powers S, Vadeboncoeur MA, Asbjornsen H. *Growth rate and water-use efficiency changes in Watershed 1 maple and birch*. Talk to be presented at the Hubbard Brook Cooperators' Meeting, July 2015.

## **Manuscripts in preparation (titles and author order subject to change)**

Vadeboncoeur MA, Green MB, Campbell JL, Asbjornsen H. *Evapotranspiration trends in large and small watersheds in the Northeastern United States*.

Vadeboncoeur MA, Asbjornsen H, Campbell JL, Green MB. *Tree physiological responses to climate variation across the Northeastern United States*.

## **Other products**

*Upon publication of the second manuscript, we will share the ring width and isotope data on the International Tree-Ring Data Base ([www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring](http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring)).*