Examining the possible causes and implications of the surprising growth resurgence of red spruce in the Northern Forest

Principal Investigator: Shelly A. Rayback
Institution: Department of Geography, University of Vermont
Email: srayback@uvm.edu
Mailing address: 207 Old Mill Bldg, 94 University Place, University of Vermont, Burlington, VT 05405
Co-Principal Investigator: Gary J. Hawley
Institution: Rubenstein School of Environment and Natural Resources, UVM
Email:ghawley@uvm.edu
Collaborator: Paul G. Schaberg
Affiliation: USDA Forest Service, Northern Research Station

Completion date: June 30, 2017

- Recent surge in red spruce growth is synchronous across the Northern Forest and likely related to declining acid deposition and warmer non-growing season temperatures
- Critical load exceedance models help to account for red spruce growth and recovery

Funding support for this project was provided by the Northeastern States Research Cooperative (NSRC), a partnership of Northern Forest states (New Hampshire, Vermont, Maine, and New York), in coordination with the USDA Forest Service.
http://www.nsrcforest.org

Project Summary

Acidic sulfur (S) and nitrogen (N) deposition depletes cations such as calcium (Ca) from forest soils and has been linked to a reduced capacity in red spruce (*Picea rubens* Sarg.) to respond to environmental stress, increases in foliar winter injury and growth declines in the northeastern United States. However, recent tree-ring-based evidence (Kosiba et al. 2014) identified a surprising reversal of decades of red spruce growth decline. This growth surge is hypothesized to be due to: 1) a decline in pollutants resulting in reduced soil acidity and the elimination of predisposing factors linked to foliar winter injury, and 2) climate change, including warmer winters and earlier springs which may reduce foliar winter injury and increase carbon capture. Two xylem increment cores were sampled from dominant or co-dominant red spruce trees at 40 sampling sites in VT, NH and MA at low, mid and high elevations. Tree-ring width chronologies were processed using standard dendrochronological techniques and converted to basal area increment (BAI) or standardized time series. Growth (BAI) differences were related to

Project Summary

modeled site-specific exceedance values and assessed using analysis of variance for the full (1950-2010), decadal and rebound (post-2003) periods to explore environmental influences on growth. Relationships between standardized tree-ring time series, climate, atmospheric carbon dioxide and pollutants were explored with correlation and response function analyses. Across all sites, recent (2001-2012) red spruce radial growth has been synchronous and above average. The critical load exceedance model helped to account for red spruce growth decline (1950-2010) and rebound from winter injury (post-2003), particularly at mid-elevation sites. Increased radial growth was also related to higher temperatures outside the growing season (fall, winter, spring) while nitrogen deposition was related to lower growth, but the strength of this relationship declined in recent years. Our research indicates increases in red spruce growth, decreases in acid deposition and increases in favorable climate conditions may result in greater carbon capture with ecological, sustainability and economic

Project Summary

benefits. The plot-based critical load exceedance model coupled with tree-ring data is informative and can help forest managers and policy makers understand and project growth of future sensitive tree species under historic and future pollutant deposition. Longer term red spruce growth trends will depend upon forest recovery from pollutant loading and future climate change. Our work also highlights the importance of scientific inquiry to identify ecological problems, the policy decisions to mitigate those issues and the evidence of resultant biological recovery.

Background

- Previous research on red spruce provides evidence for the negative influence of acid deposition on soil cation (i.e., calcium) status, predisposing trees to growth decline and mortality through a reduced capacity to respond to environmental stress.
- However, recent tree-ring-based evidence shows a reversal of decades of red spruce growth decline.
- The surprising reversal is hypothesized to be due to:
  – A decline in pollutants resulting in reduced soil acidity and the reduction of predisposing factors linked to foliar winter injury.
  – Climate change in the Northern Forest (warmer winters, earlier springs) which also may reduce foliar winter injury

Justification

Spatially- and temporally-consistent improvements in red spruce radial growth following enacted pollution reduction measures would provide policy makers with evidence of the positive effect of existing abatement policies.

If climate change benefits the growth of red spruce, then this species could again be an important component of the Northern Forest – supporting important ecological (forest health), sustainability (carbon sequestration) and economic (commercial harvesting) needs as other tree species are selected against as climate regimes shift.

Methods

- 40 sampling sites in VT, NH, MA at low (450-650m a.s.l.), mid (750-850 m a.s.l.) and high (900-1000 m a.s.l.) elevation
- Sampled two xylem increment cores per dominant or co-dominant tree (10-12 trees per site)
- Standard dendrochronological techniques used to prepare and crossdate cores (COFECHA)
- Raw tree-ring width series converted to basal area increment (BAI) (Project 1) and standardized (ARSTAN) (Project 2) time series

Methods

- **Project 1**: Differences in growth (BAI) related to modeled site-specific exceedance values (1984-1988 deposition estimates) were assessed with analysis of variance (ANOVA) for full (1950-2010), decadal, and the rebound (post-2003) periods to explore the influence of multiple environmental factors on growth.
- **Project 2**: Relationships between standardized and BAI time series (1925-2012) and climate, atmospheric carbon dioxide and pollutants were explored and modeled with correlation and response function analyses

Methods

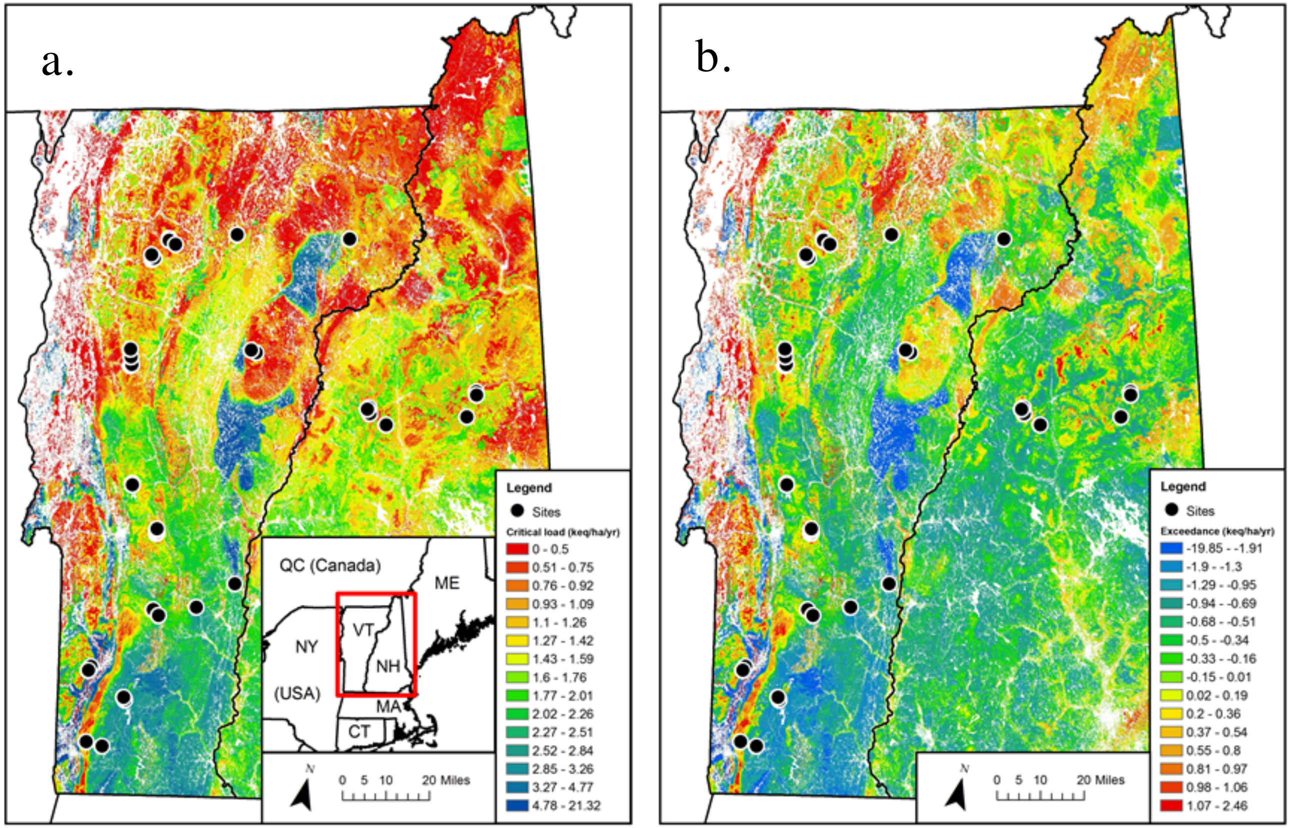

Fig. 1. Map of modeled critical load (a) and exceedance (b) of 1984-1988 sulfur and nitrogen deposition for forests in Vermont and New Hampshire (NEG/ECP 2001). Yellow to red areas indicate areas with low critical load (a) or high exceedance (b), while green to blue areas indicate increasing critical loads (a) and decreasing exceedance (b). Red spruce (*Picea rubens* Sarg.) sample sites in those states are indicated by black circles. Some sites in close proximity appear to be overlapping in this representation (Engel et al. 2016).

Results/Project Outcomes

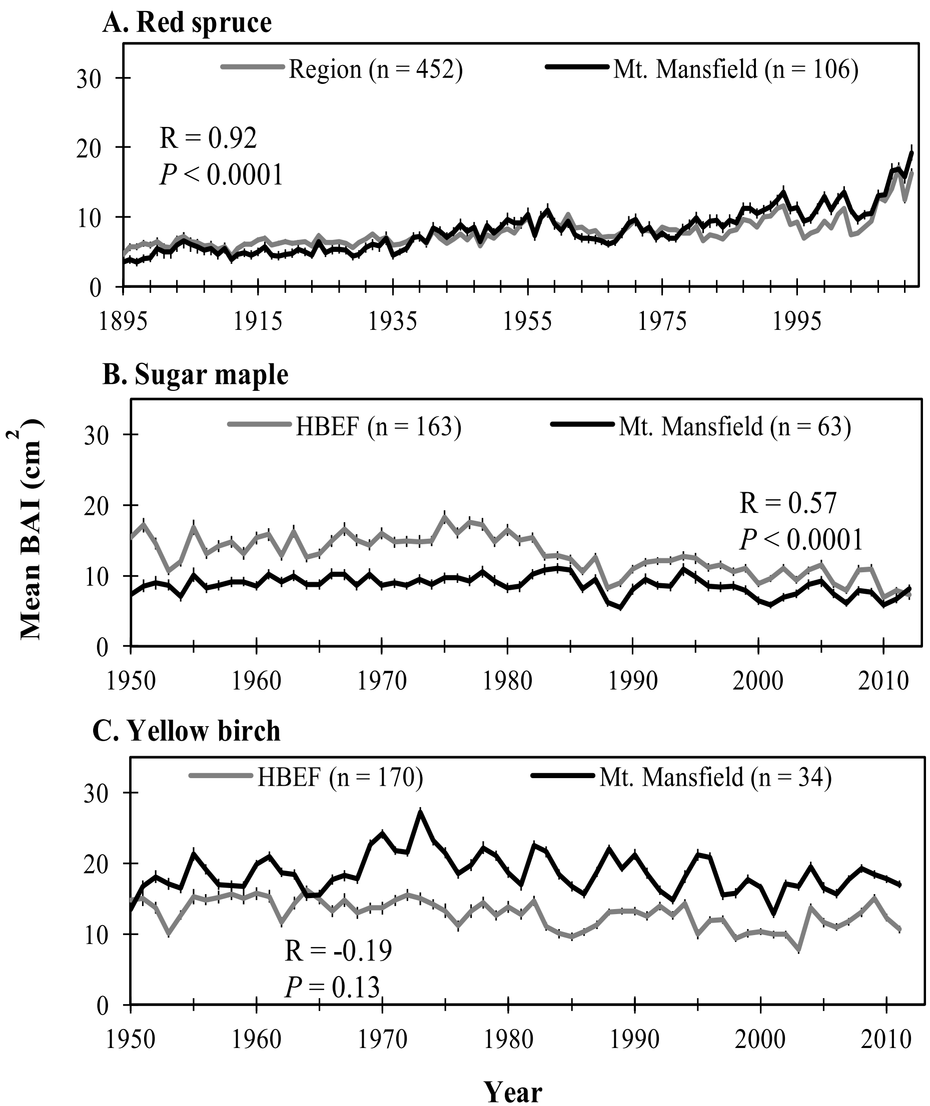

Fig 2. Comparisons of mean growth (BAI ± SD) for red spruce, sugar maple, and yellow birch from this study on Mt. Mansfield to (A) regional red spruce (34 plots in VT, NH, MA) (B) sugar maple at Hubbard Brook Experimental Forest (HBEF), NH, and (C) yellow birch at HBEF. Spearman correlation coefficients (R) and associated *P*-values are shown in each figure. Chronologies at HBEF were limited to 1950-2012 (Kosiba et al. 2016).

Results/Project Outcomes

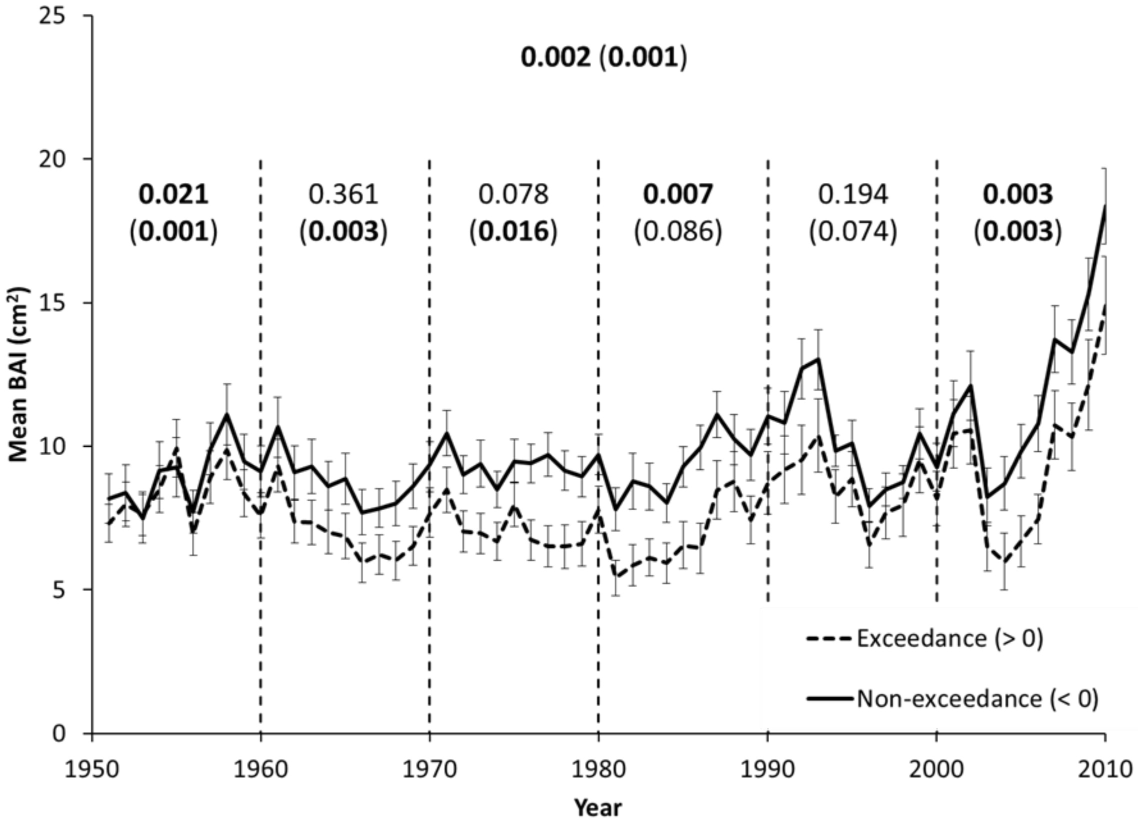

Fig. 3. Growth by sulfur and nitrogen critical load exceedance category. Mean (±SE) basal area increment (BAI) of red spruce at 37 sites in Vermont and New Hampshire that were exceeding or not exceeding modeled critical loads. The values displayed at the top of this figure are *P*-values for the influence of exceedance and the interaction between exceedance and elevation (within parenthesis), with bolded numbers indicating significant values ($P \leq 0.05$) tested using an ANOVA with year, elevation, exceedance and the interaction of elevation and exceedance as sources of variation. The model was run for the 1951-2010 period overall, and for each decade therein. The solid line represents the mean (±SE) annual BAI for sites where exceedance < 0 keq ha^{-1} yr^{-1}, while the dashed line represents the mean (±SE) for sites where exceedance > 0 keq ha^{-1} yr^{-1} (Engel et al. 2016).

Results/Project Outcomes

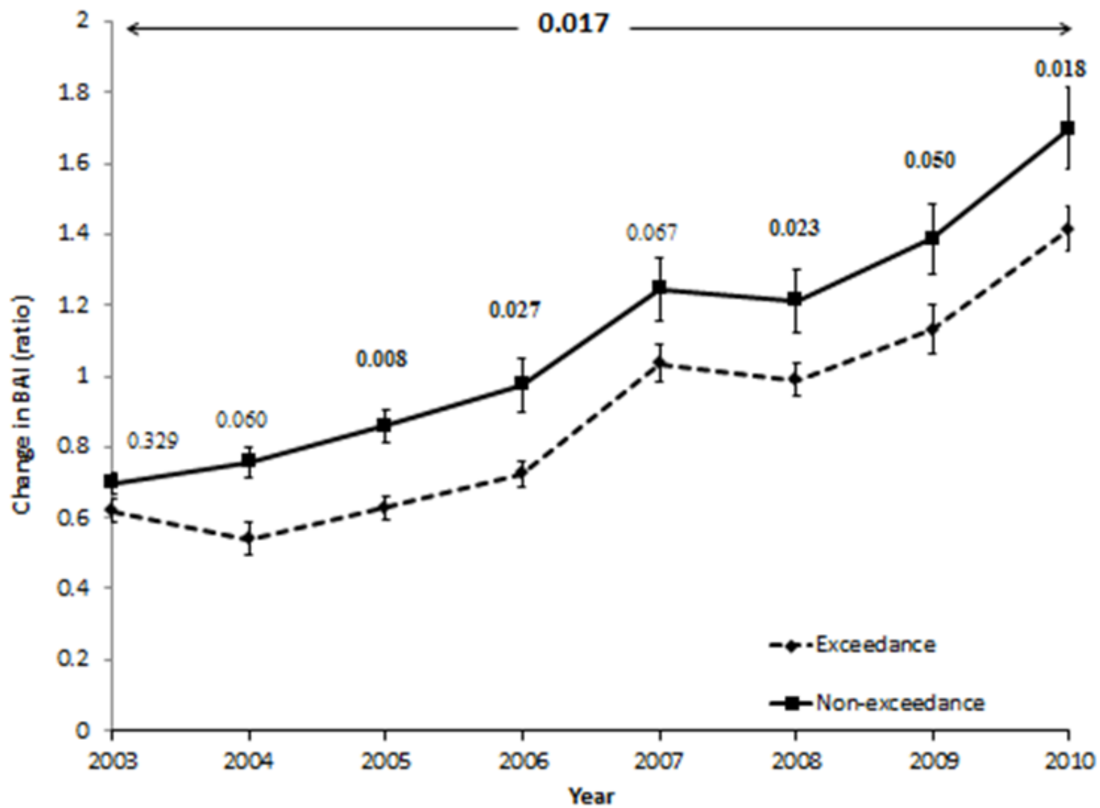

Fig 4. Growth rebound by sulfur and nitrogen critical load exceedance category. Mean (±SE) basal area increment (BAI) rebound for red spruce (*Picea rubens* Sarg.) at 37 sites in Vermont and New Hampshire following a winter injury event in 2003. The values displayed at the top of this figure are *P*-values for the influence of exceedance for the period overall (top, middle) and each year, with bolded numbers indicating significant values ($P \leq 0.05$) tested using ANOVAs with elevation and exceedance as sources of variation. Growth was standardized based on mean growth at each site in 2001-2002 (Kosiba et al., 2013), with values below 1 indicating decreased growth from that period, and values above 1 indicating growth exceeding pre-injury levels.

Results/Project Outcomes

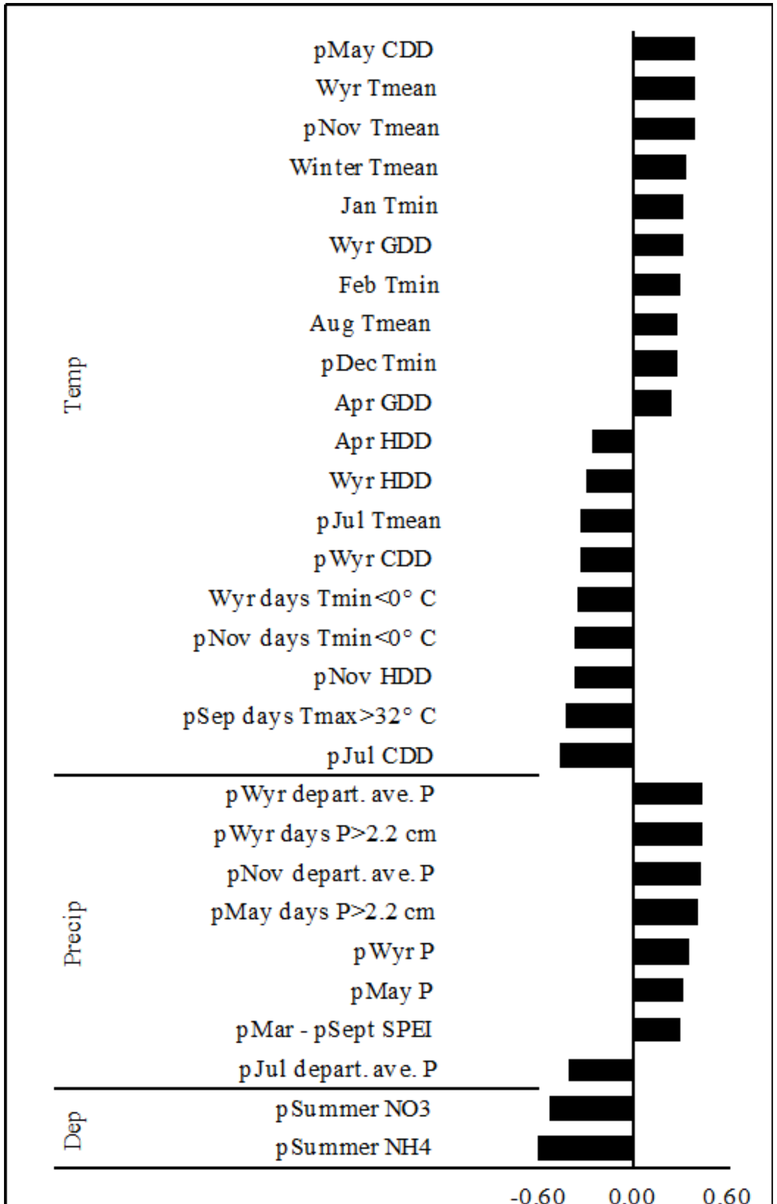

Fig 5. Significant bootstrapped climate- and deposition-growth correlations (r) with mean RWI by variable type: temperature (Temp), precipitation (Precip), and atmospheric deposition (Dep). Coefficients were considered significant if $P \leq 0.01$. Abbreviations: p =previous year, N = number, Depart.= departure, T = temperature, P = precipitation, Min = minimum, GDD = growing degree days (cumulative degrees > 5°C [41°F]), HDD = heating degree days (cumulative days < 18.3°C [65°F]), CDD = cooling degree days (cumulative degrees > 18.3°C [65°F]), Winter= previous December–February, SPEI= standardized precipitation evapotranspiration index, Wyr= water year (previous October to current September), NO3= nitrate deposition, NH4= ammonium deposition (Kosiba et al. in prep).

Summary

- Recent red spruce growth (2001-2012) across 37 Northern Forest sites is synchronous and above average since 1925
- Modeled S and N critical load exceedance can help account for red spruce growth and rebound from winter injury (2003), particularly at mid-elevation; climate is also important
- Increased growth was related to higher temperatures outside the growing season (e.g., fall, winter, spring). Nitrogen deposition was related to lower growth, but the strength of this relationship is declining

Outreach Efforts

- Results on response of red spruce growth to pollution and climate variables presented at regional, national and international conferences (ESA, ECANUSA, AGU, VMC)
- Results on response of red spruce to pollution presented to State of Vermont at the Vermont Forest Health Meeting
- Report submitted to Vermont Monitoring Cooperative (now Forest Ecosystems Monitoring Cooperative) on trends in red spruce and other tree species' growth and their response to climate change and pollution abatement
- Presentation of project results to public via NSRC webinar
- Development of the Dendroecological Database; NSRC-sponsored research (tree-ring chronologies and associated metadata will be archived there (hosted by FEMC)
- Two peer-reviewed manuscripts published; two *in prep*

Implications and applications in the Northern Forest region

- Based on recent evidence of red spruce radial growth, decreases in acid deposition and increases in favorable climate conditions, red spruce trees may increase C capture with ecological and economic benefits. Longer term growth trends will likely depend upon future climate change.

- Plot-based critical load exceedance models coupled with tree-ring growth data may be informative to forest managers and policy makers trying to understand and project the growth of sensitive tree species under historic and changing pollutant deposition loads.

Implications and applications in the Northern Forest region

- More broadly, this work demonstrates the importance of scientific inquiry to identify ecological problems (here acid deposition-induced decline), policy decisions to mitigate those issues (the Clean Air Act and subsequent amendments), and evidence of resultant biological recovery.

Future directions

- Continued monitoring of red spruce growth for evidence of continued recovery
- Application of critical load exceedance model to other sensitive tree species (e.g., sugar maple) in the Northern Forest
- Exploration of growth trends of other Northern Forest tree species across time and space and their responses to climate change and decreasing pollutant inputs.
- Investigation of the effects of climate change and pollutant legacies on water use efficiency and carbon storage in red spruce and other tree species.

List of products

Peer-reviewed papers

Engel, B.J., Schaberg, P.G., Hawley, G.J., Rayback, S. A., Pontius, J., Kosiba, A.M., Miller, E.K. 2016. Assessing relationships between red spruce radial growth and pollution critical load exceedance values**.** *Forest Ecology and Management* 359: 83-91. doi: 10.1016/j.foreco.2015.09.029.

Kosiba, A., Schaberg, P.G., Rayback, S.A**.** and Hawley, G.J. 2017. Comparative growth trends of five Northern hardwood and montane species reveal divergent trajectories and response to climate. *Canadian Journal of Forest Research*. 47: 743-754.

Kosiba, A., Schaberg, P.G., Rayback, S.A., Hawley, G.J. (in prep) Exploring possible causes for the surprising recovery of red spruce growth in the northern United States. To be submitted to: *Global Change Biology*.

Schaberg, P.G., Kosiba, A.M., Hawley, G.J., Rayback, S. A., Pontius, J., Miller, E.K., Engel, B.J. (in prep). Pollutant critical load exceedance – do deposition legacies matter. To be submitted to: *Canadian Journal of Forest Resources*.

List of products

Other publications

Engel, B.J., 2014. *Investigating the relationship between modeled calcium depletion and red spruce growth and response to environmental stress***.** Burlington, VT: University of Vermont. 68p. M.Sc. Thesis.

Kosiba, A. 2017. *Quantifying tree response to alterations in pollution deposition and climate change in the Northeastern US*. Burlington, VT: University of Vermont. 187p. Ph.D. Thesis.

Kosiba, A.M., Schaberg, P.G., Hawley, G.J., Rayback, S.A. 2014. *Using dendrochronological techniques to interpret the response of trees to environmental change at the Vermont Monitoring Cooperative's Mount Mansfield study site***.** Report to the Vermont Monitoring Cooperative, July 2014, 57p. (http://www.uvm.edu/vmc/project/developing-multiproxy-tree-ring-based-reconstruction)

List of products

Presentations

Schaberg, P.G., S. Rayback, C. Hansen, P. Murakami, J. Duncan, Jennifer Pontius, A. Kosiba, R. Stern, G. Hawley. 2017. Tree growth and response to environmental conditions. Vermont Forest Health Information Meeting, Woodstock, VT, April 19, 2017.

Kosiba, A.M., Schaberg P.G., Rayback S.A., Hawley G.J. *Linking climate and environmental factors to the recent and surprising growth increase of red spruce trees across the northeastern US*. American Geophysical Union Fall Meeting San Francisco, CA. December 12, 2016

Schaberg, P.G., Kosiba, A.M., Engle, B.J., Hawley, G.J., Rayback, S.A., Pontius, J., Miller, E.K. 2016. *Pollution critical load exceedance and an extended growing season as modulators of red spruce radial growth*. American Geophysical Union Fall Meeting. San Francisco, CA. December 12, 2016.

List of products

Presentations

Kosiba, A.M., Schaberg, P.G., Rayback, S.A., Hawley, G.J. 2016. *Investigating the surprising, recent growth increase of red spruce trees across the region*. ECANUSA Meeting, Burlington, VT. September 30, 2016.

Schaberg, P.S., Rayback, S.A., Hawley, G.J., Pontius, J., et al., 2015. *Tree Growth Trends: Developing a Dendrochronological Database for the Northern Forest.* Vermont Monitoring Cooperative (VMC) Annual Meeting. December 2015.

Kosiba, A., Schaberg, P.G., Rayback, S. A., Hawley, G. J. 2015. *Using dendroecological techniques to interpret the response of trees to environmental change at Vermont Monitoring Cooperative's Mount Mansfield study site.* Ecological Society of America Annual Meeting, Balitmore, MD. August 2015.

List of products

Presentations

Kosiba, A.M. Schaberg, P.G. Hawley, G.J. Rayback, S.A. 2014. *Using dendrochronological techniques to interpret the response of trees to environmental change at VMC's Mount Mansfield study site*. Vermont Monitoring Cooperative Annual Meeting, December 11, 2014, Burlington, VT. Page 60 in Pontius, J., J. Duncan, M. Pendleton, J. Rosovsky, and C. Waite (Eds.) 2015. *Science to Policy: Benefitting from Actionable Science*. Proceedings of the December 11, 2014 Vermont Monitoring Cooperative and Mt. Mansfield Science and Stewardship Conference: Burlington, VT, Vermont Monitoring Cooperative. Available online at http://www.uvm.edu/vmc/annualMeeting/2014/proceedings.

Schaberg, P.G.; Engel, B.J.; Hawley, G.J.; Rayback, S.A.; Pontius, J.; Kosiba, A.M.; Miller, E.K. 2015. Assessing a 60-year red spruce radial growth chronology relative to pollution critical load exceedance values. Ecological Society of America (ESA) 100th Annual Meeting, Baltimore, MD, August 10.

List of products

Presentations

Rayback, S.A. Schaberg, P.G. Lini, A. Hawley, G. Halman, J. 2014. *The tree-ring perspective: How dendrochronological techniques enhance study of environmental change in New England***.** Vermont Monitoring Cooperative Annual Meeting, December 11, 2014, Burlington, VT. Page 58 in Pontius, J., J. Duncan, M. Pendleton, J. Rosovsky, and C. Waite (Eds.) 2015. *Science to Policy: Benefitting from Actionable Science*. Proceedings of the December 11, 2014 Vermont Monitoring Cooperative and Mt. Mansfield Science and Stewardship Conference: Burlington, VT, Vermont Monitoring Cooperative. Available online at http://www.uvm.edu/vmc/annualMeeting/2014/proceedings

Schaberg, P.G. Hawley, G.J. Rayback, S.A. Kosiba, A.M. 2014. *Deciphering the mysterious resurgence of red spruce***.** Vermont Forest Health Information Meeting, Vermont Forests, Parks and Recreation, Woodstock, VT, April 16, 2014.

List of products

Presentations

Schaberg, P. Engel, B. Hawley, G. Rayback, S. Kosiba, A. Pontius, J. Miller. E. 2013. *A preliminary analysis of relationships between red spruce woody growth and high-resolution pollution critical loads and exceedance values for Vermont and New Hampshire***.** Vermont Monitoring Cooperative Annual Meeting, Burlington, VT, December 12, 2013.

List of products

Webinars

Rayback, S. A., Kosiba, A. M., Schaberg, P.S., Engle, B., Hawley, G.J. 2016. *Examining the possible causes and implications of the surprising growth resurgence of red spruce in the Northern Forest*. Northeastern States Research Cooperative Webinar. University of Vermont. December 21, 2016.

Databases

The Dendroecological Database (in prep). Hosted by: The Forest Ecosystem Monitoring Cooperative (formally The Vermont Monitoring Cooperative) (https://www.uvm.edu/femc/). Online: Fall 2017.