The Vermont Forest Ecosystem Management Demonstration Project: Evaluation of Carbon and Methane Responses One Decade Post-Treatment

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Yale University, School of Forestry and Environmental Studies

Completion date: 6/30/17

Structural complexity enhancement (SCE) treatments in northern hardwood-conifer forests resulted in carbon storage only slightly less than simulated no-harvest baselines, and substantially greater than conventional selection harvest systems. SCE demonstrated utility, therefore, as a forest management approach providing carbon storage as well as other co-benefits including timber. Methane emissions from the heartwood of older trees of some species could reduce the average climate mitigation value of temperate forests by 10-30%, though there is still high scientific uncertainty around this question.

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http://www.nsrcforest.org

Project Summary

Forest management practices emphasizing stand structural complexity are of interest across the northern forest region of the United States because of their potential to enhance carbon storage while producing other co-benefits including wood products. Our research is part of a long-term study evaluating silvicultural treatments that promote late-successional forest characteristics in northern hardwood-conifer forests. We are testing the hypothesis that aboveground biomass development (carbon storage) is greater in structural complexity enhancement (SCE) treatments when compared against selection systems (single-tree and group) modified to retain elevated structure. Manipulations and controls were replicated across 2-hectare treatment units at two study areas in Vermont, USA. Data on aboveground biomass pools (live trees, standing dead, and downed wood) were collected pre- and post-treatment then again a decade later. We used the Forest Vegetation Simulator to project "no-treatment" baselines specific to treatment units, allowing measured carbon responses to be normalized against differences in site characteristics affecting tree growth and pre-treatment stand structure.

Results indicate that 10 years post-treatment biomass development and carbon storage were greatest in SCE treatments compared to conventional treatments, with the greatest increases in coarse woody material pools. Percentage differences between post-treatment carbon and the simulated baselines indicate that carbon pool values in SCE treatments returned closest to pre-harvest or untreated levels over conventional treatments. Total carbon storage in SCE aboveground pools was 15.90% less than that projected for no-treatment compared to 44.94% less in conventionally treated areas. Structural complexity enhancement has the potential to increase carbon storage in managed northern hardwoods. It, and similar approaches, offer an alternative for sustainable management integrating carbon, associated climate change mitigation benefits, and late-successional forest structure and habitat.

This study contributed data to a large-scale (eastern U.S. states) study by cooperators at Yale University on methane production in the heartwood of larger diameter trees. That study found that trunk methane concentrations can reach as high as 67.4% by volume, with the highest concentrations found in older angiosperms. Methane emissions from the trunk-based methanogenic pathway could reduce the average climate mitigation value of these temperate forests by 10-30%, but this is an area requiring more extensive investigation.

Background and Justification

Introduction

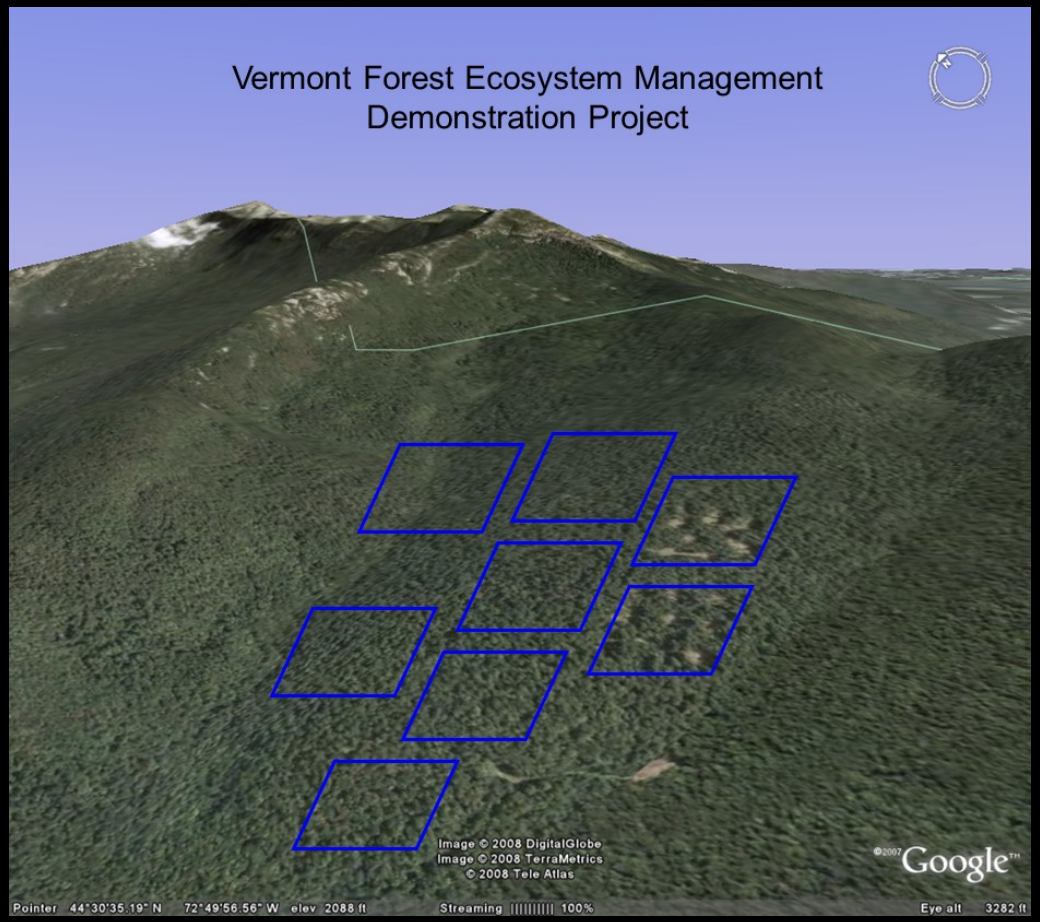
The Vermont Forest Ecosystem Management Demonstration Project (FEMDP) brings together researchers from diverse fields in an experimental test of "structure-" or "natural disturbance-based" silvicultural approaches. Structure-based forestry focuses on the architecture of forest ecosystems at both stand-level and landscape-level spatial scales. Disturbance-based silviculture attempts to approximate the range of structural and compositional conditions associated with natural disturbance regimes. These approaches share the operational objective of managing for currently under-represented forest structures and age classes. They have recently gained additional attention because of their potential utility for maintaining high levels of biomass in managed forests, which is currently incentivized by rapidly developing compliance and voluntary carbon markets. This study evaluated for ability of a silvicultural treatment called "Structural Complexity Enhancement (SCE)" to maintain high levels of biomass and accelerate rates of stand development leading to future carbon accumulations.

In the northern hardwood region of eastern North America a structure or disturbance-based approach would include managing for late-successional structure, which is vastly under-represented relative to pre-European settlement conditions. The FEMDP has tested the hypothesis that silvicultural practices can accelerate rates of late-successional forest stand development, promote desired structural characteristics, and enhance associated ecosystem functions more than conventional systems. We have tested this hypothesis using an approach (SCE) that promotes old-growth characteristics while also providing opportunities for low-intensity timber harvest. SCE was compared against uneven-aged systems (single tree and group selection) that also have utility for producing structurally complex stand conditions. The uneven-aged prescriptions employed in this study were modified to increase post-harvest structural retention. In addition, group-selection treatments were modified to approximate the average canopy opening size associated with fine-scale natural disturbance events in the northeastern United States.

Background and Justification

Study Goals

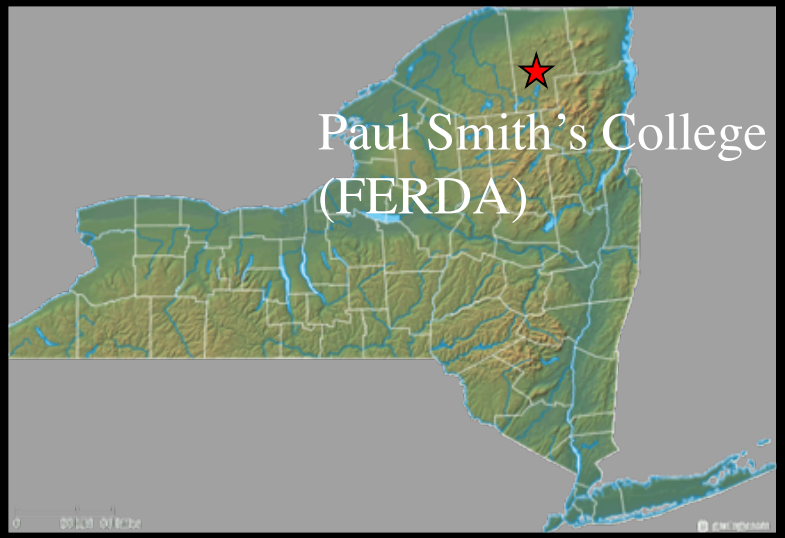
- Reinitiate the Vermont Forest Ecosystem Management Demonstration Project (FEMDP),
- Assess carbon flux and co-varying habitat responses to experimental treatments using annual data collected over more than a decade post-harvest.
- Validate previously generated carbon storage and sequestration predictions, including carbon fluxes among multiple aboveground pools (e.g. live trees, standing dead, downed woody debris, etc.).
- Inform sustainable forest management practices for a range of late-successional forest ecosystem services, including tradeoffs and complementarity among timber, carbon sequestration/climate mitigation, and biodiversity.
- Contribute data on methane production and flux in tree heartwood to a larger study (eastern U.S.) of methanogenic processes.



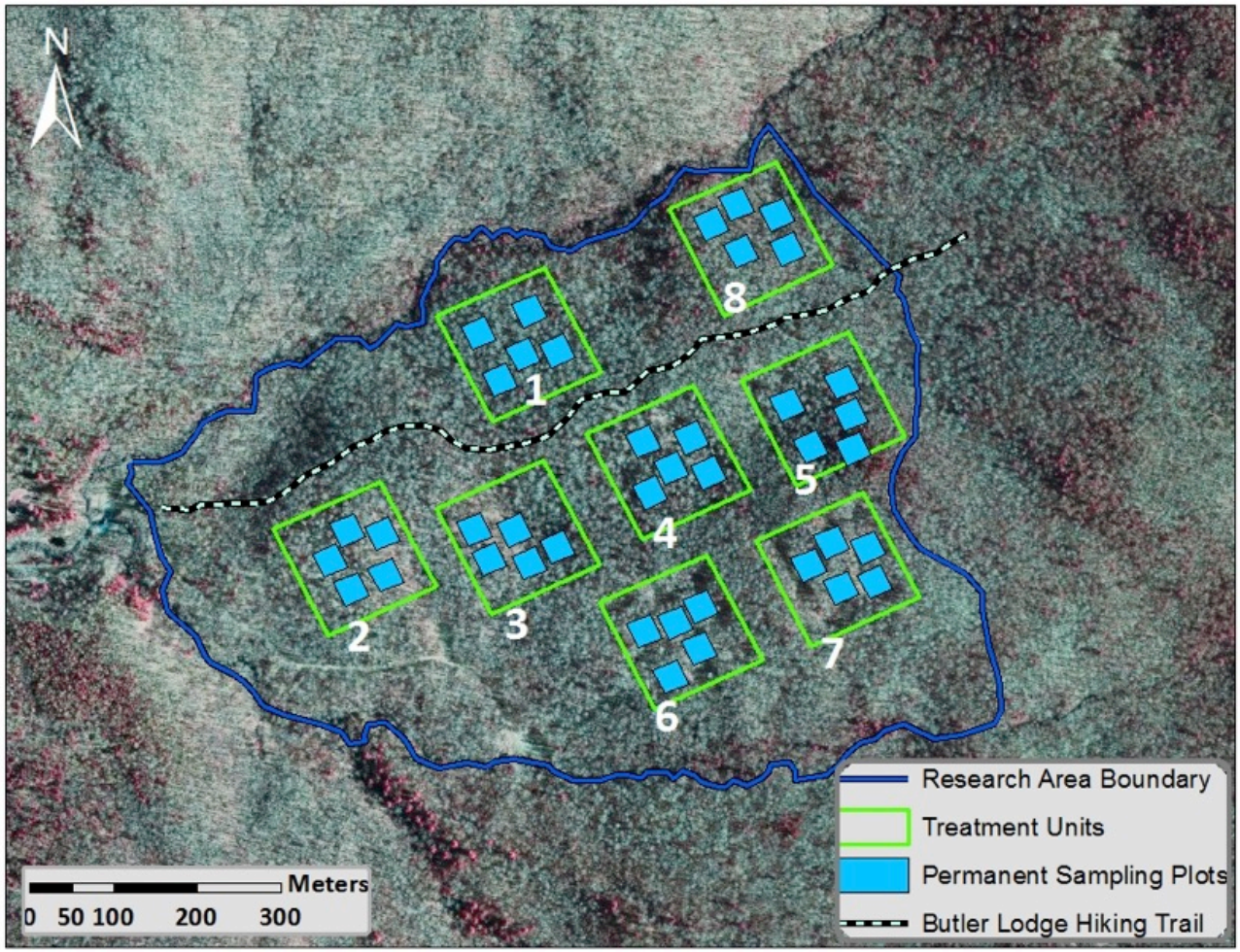
METHODS:
Forest Ecosystem Management Demonstration Project

Study Sites

- Mature, multi-aged northern hardwoods
- History of thinning and selection harvesting
- Mid-elevation, moderate productivity
- FERDA (NY) sites shared data for similar control and selection treatments only



Experimental Design

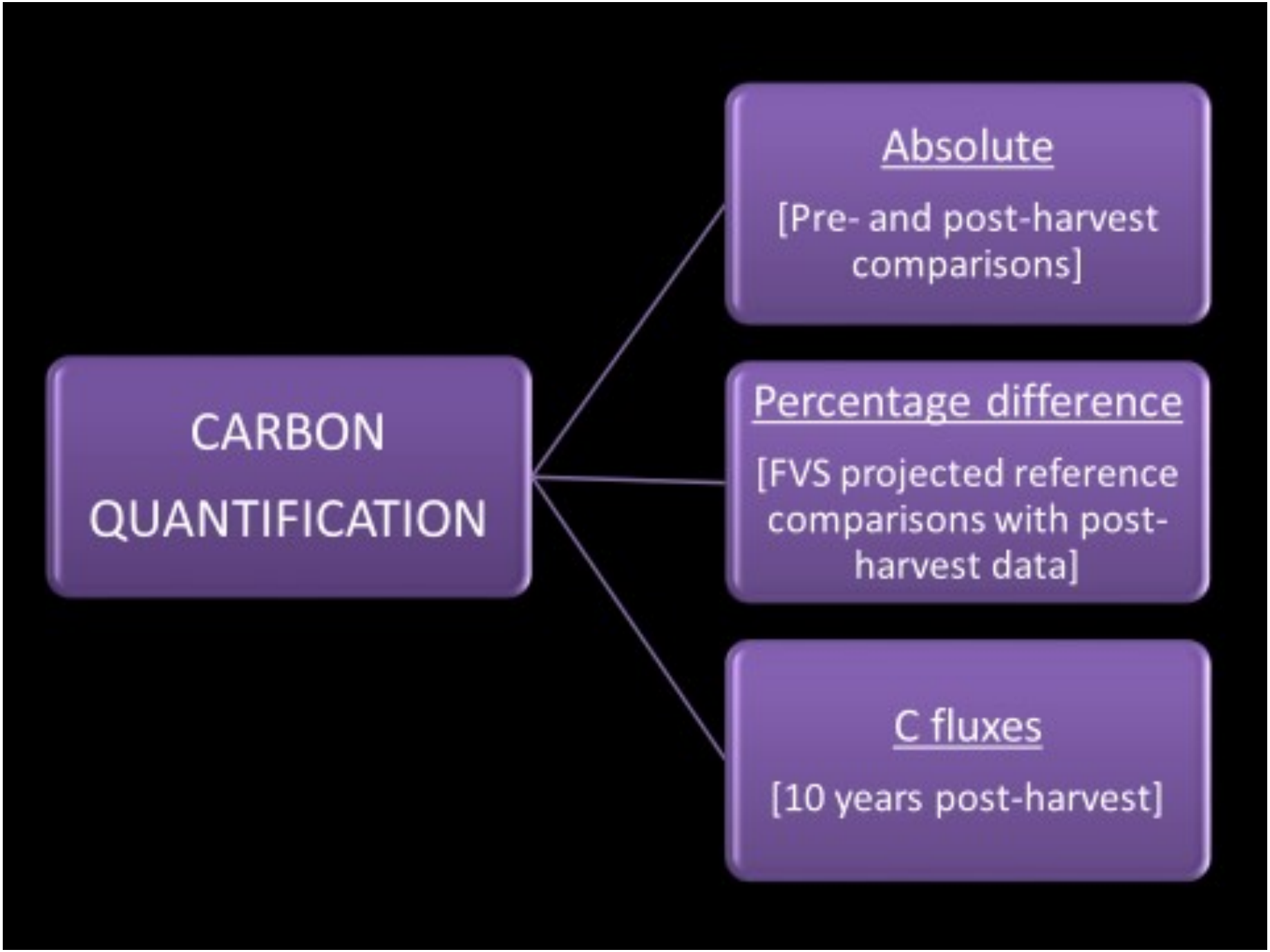


2 ha treatment units

0.1 ha permanent plots

- Prescriptions for treatments evaluated in the FEMDP. To make it a "fair" test, the study compared Structural Complexity Enhancement (SCE) against conventional selection systems modified to retain more structure, particularly in medium and larger tree size classes, than is often typical. The target basal area (post-harvest for selection treatments; desired in the future for SCE), maximum tree diameter retained post-harvest (selection treatments) or desired in the future (SCE), and q-factor define the shape of the residual (or post-harvest) diameter distribution. For SCE, the variable q factor approximated the rotated sigmoid distribution sometimes found in old-growth forests. The conventional treatments employed negative exponential distributions.

Treatment	Target residual basal area (m^2 ha^{-1})	Max diameter (cm)	*q*-factor†	Structural objective	Silvicultural prescription
SINGLE-TREE SELECTION	18.4	60	1.3	Structural retention	• Modified residual basal area and diameter distribution
				Vertically differentiated canopy	• Release advance regeneration • Regenerate new cohort
GROUP SELECTION	18.4	60	1.3	Structural retention	• Modified residual basal area and diameter distribution
				Vertically differentiated canopy	• Release advance regeneration • Regenerate new cohort
				Horizontal diversification	• Spatially aggregated harvest (patches ~ 0.05 ha)
STRCTURAL COMPLEXITY ENHANCEMENT	34	90	2.0/1.1/1.3	Re-allocation of basal area to larger size class	• Rotated sigmoid diameter dist. • High max d and target basal area • Retention of trees >60 cm dbh
				Vertically differentiated canopy	• Release advance regeneration • Regenerate new cohort
				Horizontal diversification	• Variable density tree marking • Small gaps (~ 0.02 ha) around crown released trees
				Dampened growth decline in larger trees	• Full (3- or 4-sided) and partial (2-sided) crown release
				Elevated coarse woody material volume and density	• Tree girdling to create snags • Felling and leaving trees to create downed logs • Pushing or pulling trees over to create tip-up mounds


CARBON QUANTIFICATION
Absolute
[Pre- and post-harvest comparisons]
Percentage difference
[FVS projected reference comparisons with post-harvest data]
C fluxes
[10 years post-harvest]

Absolute Carbon Quantification

- **Live tree**
  - Allometric equations in NED-3 (Jenkins et al. 2003)
- **Downed log**
  - Volumetric calculations with density decay class adjustments (Harmon et al. 2009)
- **Standing dead**
  - Structural deductions and decay class adjustments (Jenkins et al. 2003, Harmon et al. 2011, CARB 2014)

Baseline Comparisons and Fluxes

- **'Baseline' live tree** conditions projected with FVS (Forest Vegetation Simulator)
- **Baseline standing dead and downed log** conditions equal to pre-harvest inventory
- **Percentage differences** comparing post-harvest and baselines (Littlefield and Keeton 2012, Westerling et al. 2006)

$$[(V_H - V_B)/((V_H + V_B)/2)] * 100$$

V_H = harvest C; V_B = baseline C

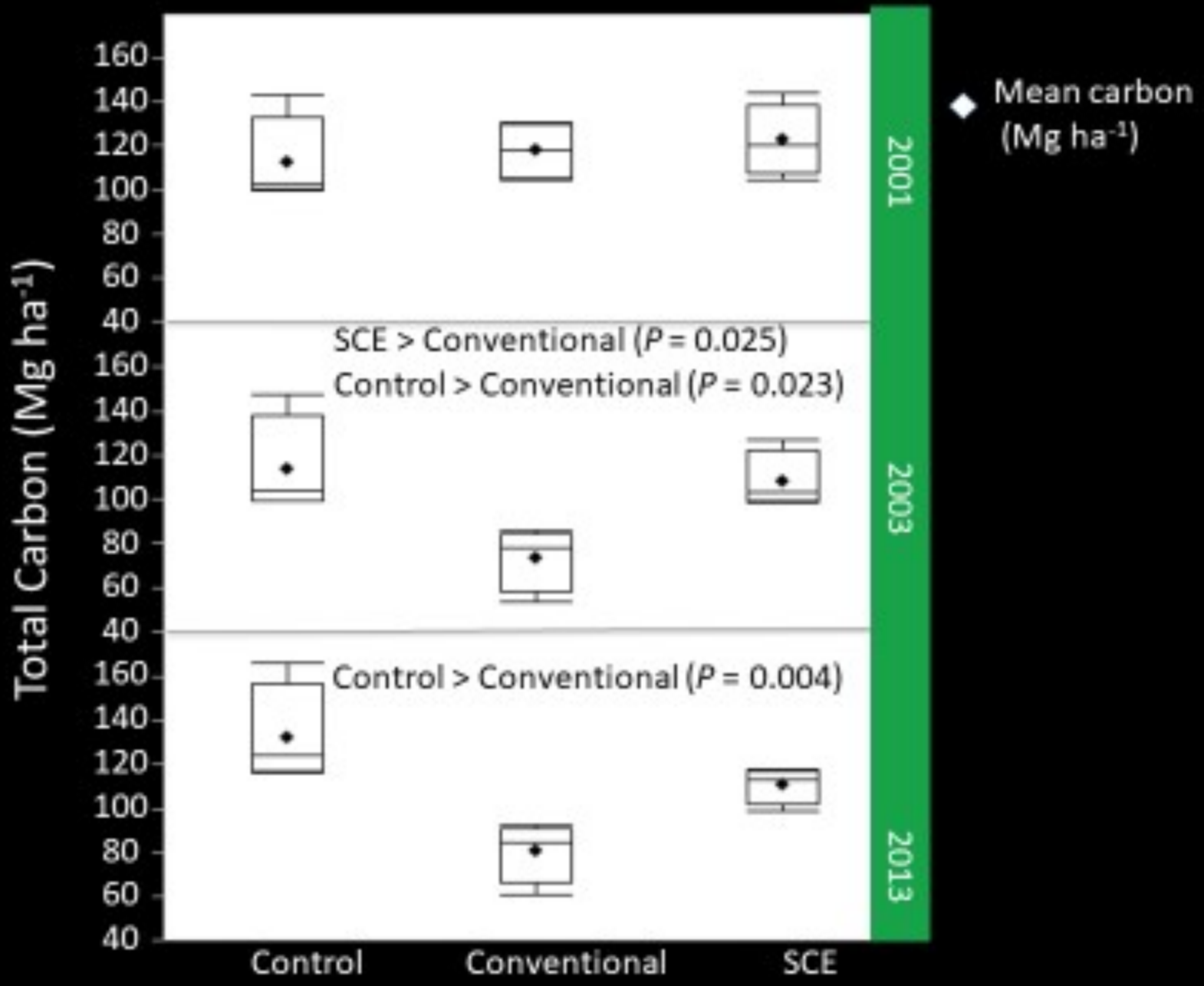
- **Fluxes** equal to gain or loss in carbon in 10-year interval post-harvest (for each pool) (Harmon 2001, Russell et al. 2014)

Results

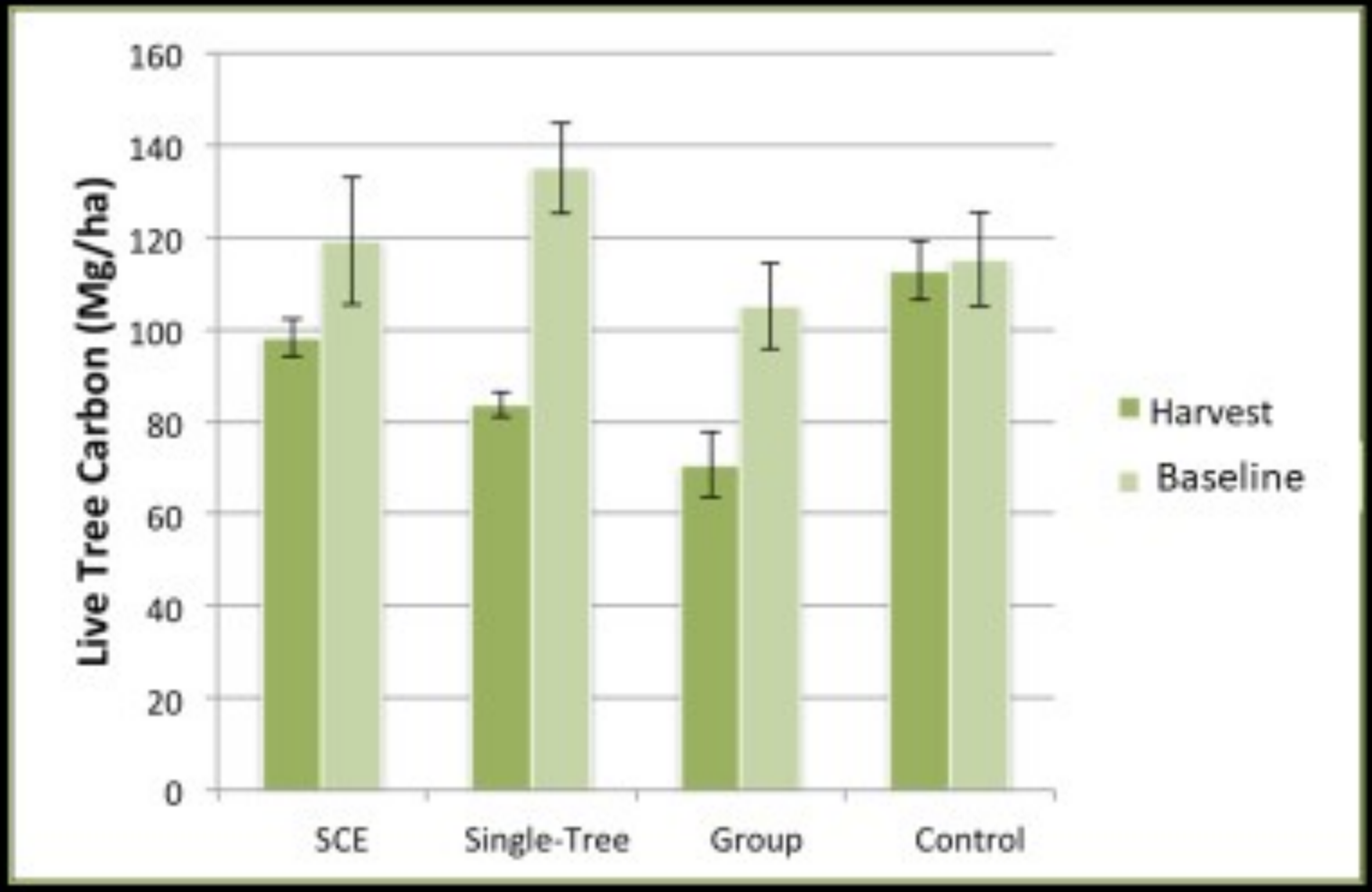
Structural Complexity Enhancement unit, UVM Research Forest, VT., July 2017

Structural Complexity Enhancement unit, Mt. Mansfield State Forest, VT. June 2014

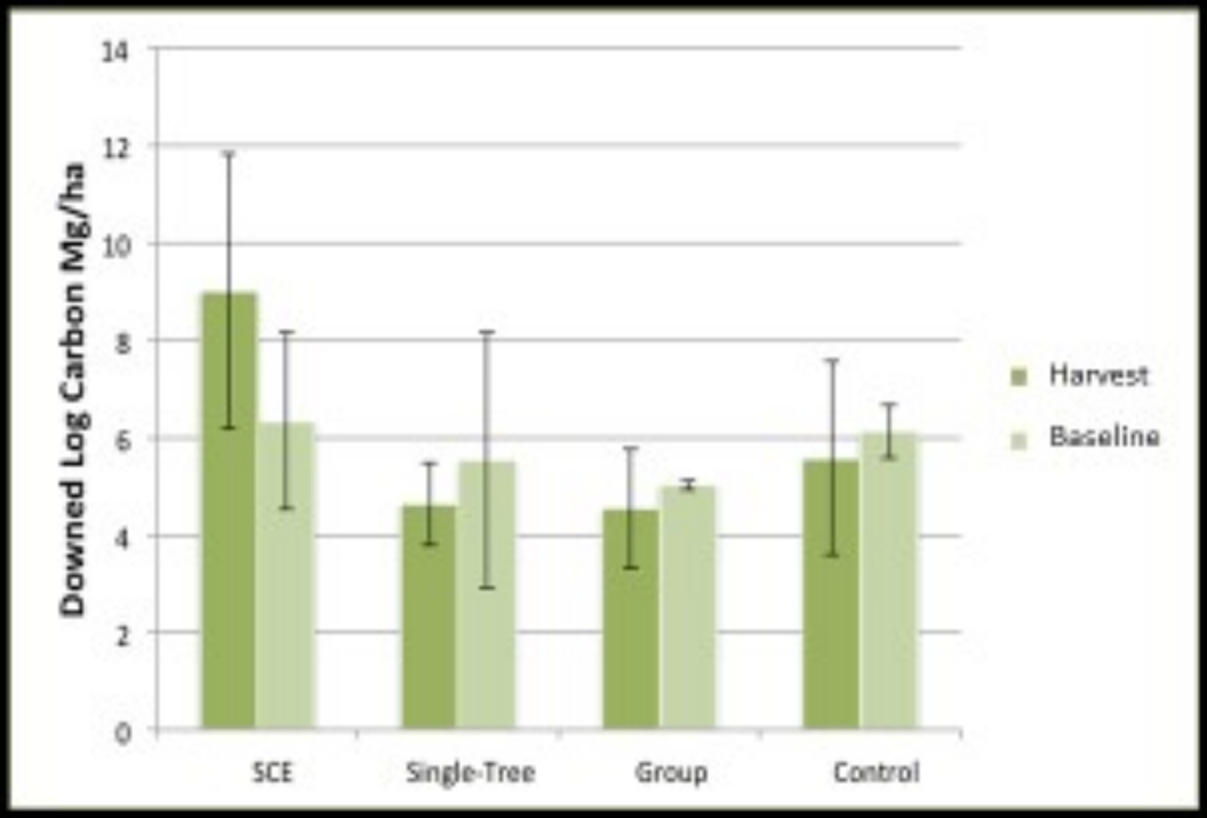
Absolute Comparisons: TOTAL C



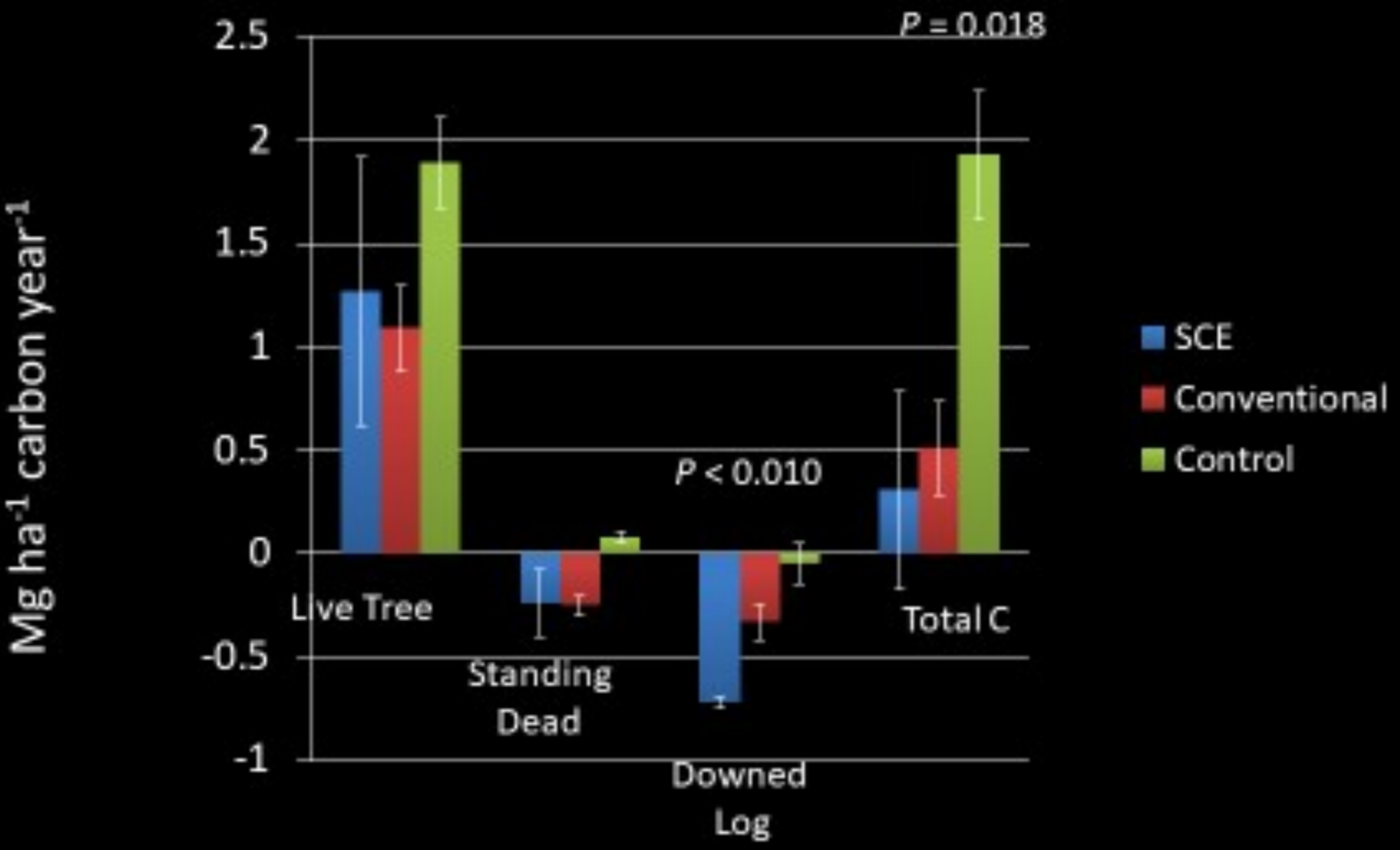
Harvest-baseline comparisons: LIVE TREE carbon pool



Harvest-baseline comparisons: DOWNED LOG carbon pool



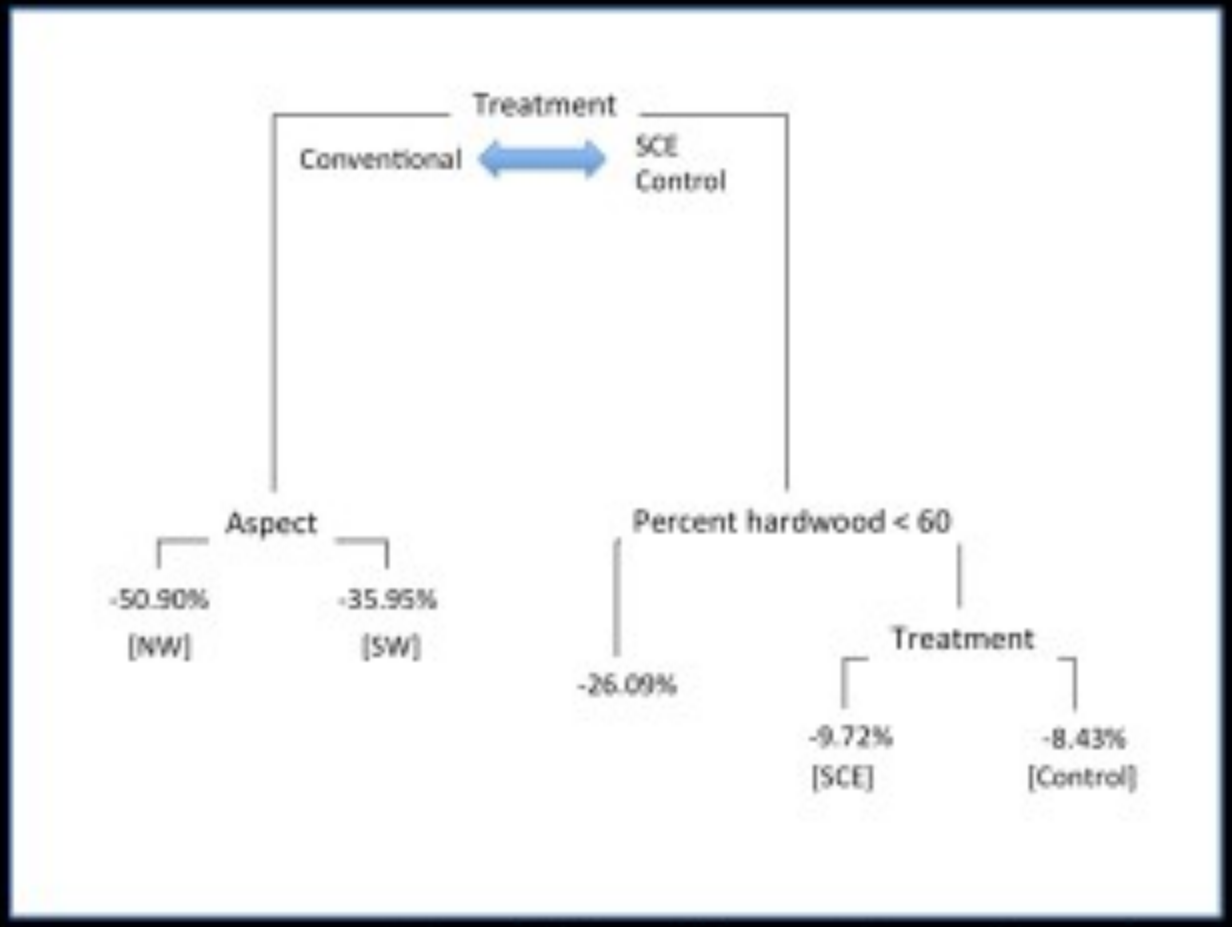
Carbon fluxes post-harvest



Greatest C fluxes in SCE treatments in live tree and downed log pools

Classification and Regression Tree:

- Ranking of variables explaining the percent difference in live tree carbon 10 years post-treatment
- The dependent variable (%) is the percent difference between the measured treatment outcomes and the simulated no-harvest baseline for each treatment unit

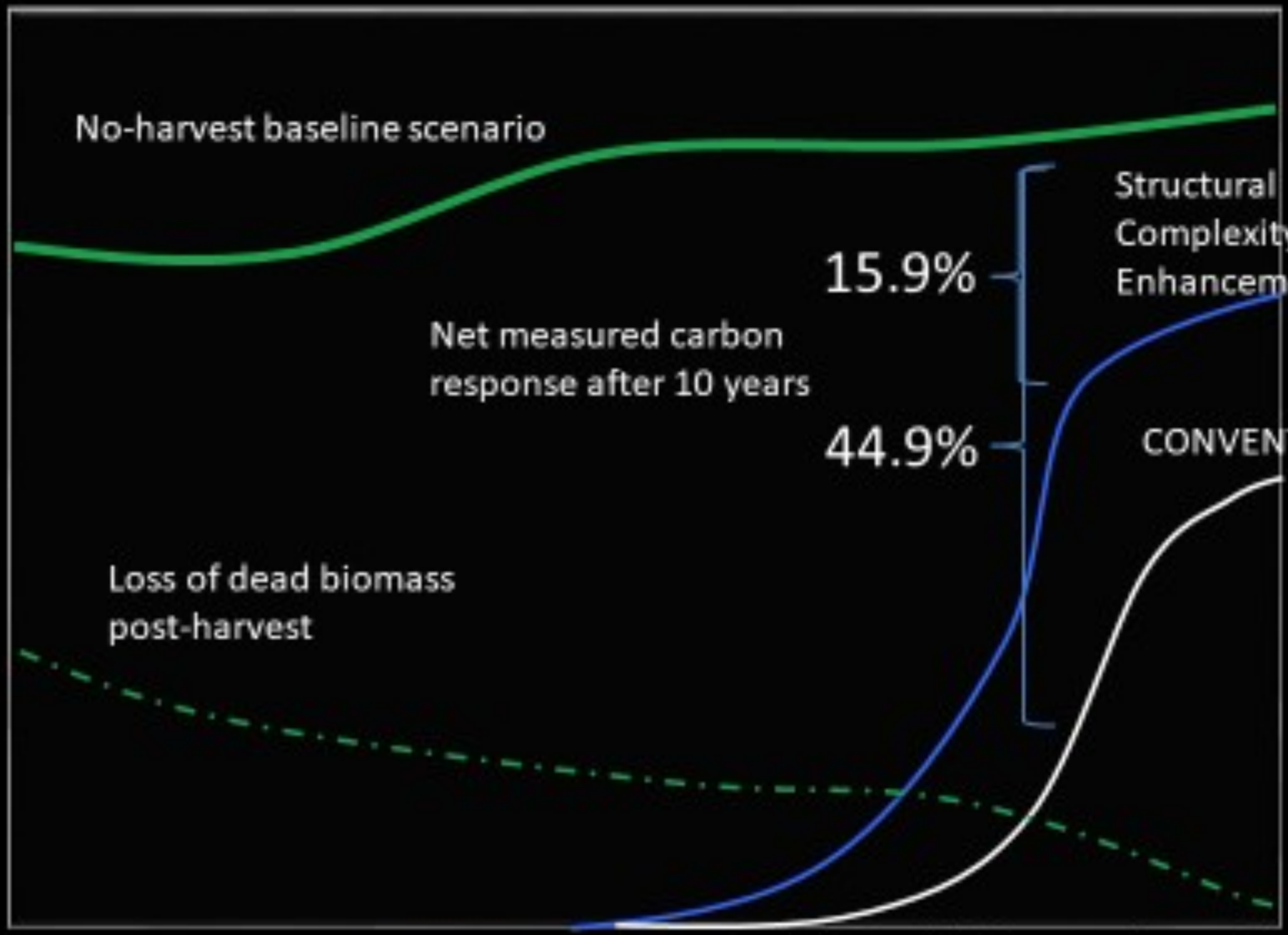


Top ranked variables:

- Treatment
- Aspect
- Percent hardwood

n = 18; α = 0.01; minimum observations = 2

- Support for earlier hypotheses in the literature regarding carbon value of SCE
- SCE recovers closer and more rapidly to non-harvest baseline



Trend lines modified from Bauhus et al. (2009). For. Ecol. & Mgt.

PROJECT OUTCOMES

- 6 peer-reviewed journal papers
- 1 book
- 2 book chapters
- 2 masters theses
- 1 undergraduate honors thesis
- 3 leveraged grants
- 18 invited conference or workshop presentations and legislative testimony
- 6 contributed conference or workshop presentations
- 2 webinars
- 1 Radio interview (VPR, NPR Boston, and NPR “Here and Now”)
- 6+ Popular press articles

Brasov, Romania, Sept. 2016. Presentation on global old-growth silviculture, conservation, and management for the General Secretariat of the Carpathian Convention

Implications and applications in the Northern Forest region

- Structural complexity enhancement treatments are an effective approach for increasing carbon storage in managed northern hardwoods. They offer an alternative for sustainable management integrating carbon, associated climate change mitigation benefits, and late-successional forest structure and habitat.

- Management systems incorporating structural complexity into integrated operations can increase the contribution of working forests to climate change mitigation, helping to moderate the intensity of future climate change. They can be incorporated into integrated forest management, thereby helping to achieve a full range of ecosystem goods and services from working forests in the northern forest region.

- Disturbance-based management promoting legacy tree retention, inputs to coarse woody debris pools, increased vertical and horizontal heterogeneity, and elevated biomass levels are options for maximizing carbon storage potential. These provide important co-benefits in terms of habitat function and biodiversity conservation targeted at the full array of temperate forest species, including those associated with late-successional habitats.

- Techniques like those tested in the study, namely Structural Complexity Enhancement, can be used by landowners in the northern forest region that are interested in participating in carbon markets through improvement forest management projects. This has the potential to add additional revenue to working forests, thereby incentivizing sustainable forest management and open space conservation.

- Remaining cognizant of the potential for late-successional compositional and structural baselines to shift over time with global change – including climate impacts on forest growth and disturbance regimes, altered species ranges, and the effects of invasive species – will be important for adaptive management for late-successional functions such as carbon storage.

Future directions

- Continue to re-measure and monitor the permanent plot systems at the FEMDP sites as funding allows.
- Raise grant funding to implement deer exclusion and beech control experimental treatments. This would employ a split plot design superimposed on the current design.
- Integrate Structural Complexity Enhancement with silvicultural approaches promoting flood resilience. Scale experimentally to stream reach and watershed scales if funding becomes available.
- Apply results to the development of demonstration forest carbon projects in the northern forest region, helping landowners to add revenue to working forests.

List of products

Peer-reviewed journal papers:

Fahey, R.T., B. C. Alvesherea, J.I. Burton, A.W. D'Amato, Y.L. Dickinson, W.S. Keeton, C.C. Kerne, A.J. Larson, B.J. Palik, K.J. Puettmann, M.R. Saunders, C.R. Webster, J.W. Atkins, C.M. Gough, and B.S. Hardimani. Shifting conceptions of complexity in forest management and silviculture. *In Press*. Forest Ecology and Management https://doi.org/10.1016/j.foreco.2018.01.011

Ford, S.E. and W.S. Keeton. 2017. Enhanced carbon storage through management for old-growth characteristics in northern hardwoods. Ecosphere 8:1-20.

Gottesman, A. and W.S. Keeton. 2017. Regeneration responses to management for old-growth characteristics in northern hardwood-conifer forests. Forests 8 (45): 1-21.

Covey, K. R., C. A. Bettigole, R. J. Warren, C. A. Williams, H. Gu, D. P. Aubrey, H. Asbjorsen, K. K. Bohn, A. T. Classen, T. W. Crowther, M. Farrell, B. R. Frey, E. J. Holzmueller, W. S. Keeton, B. O. Knapp, Jos. R. King, Karen K. Kuers, J. M. Lhotka, J. P. Love, D. S. Maynard, J. P. Megonigal, S. Pitz, N. E. Ruttenbeck, N. Sanders, M. R. Saunders, J. P. Stovall, K. Szlavecz, J. P. Wright, N. Wurzburger, C. D. Oliver, X Lee1, and M. A. Bradford. Living trees are a major source of methane in temperate forests. Nature Climate Change, in review

Kern, C. C., J. Burton, P. Raymond, A. D'Amato, W.S. Keeton, A.A. Royo, M.B. Walters, C.R. Webster, and J.L. Willis. 2016. Challenges facing gap-based silviculture and possible solutions for mesic northern forests in North America. Forestry 90: 4-17.

Dove, N.C and W.S. Keeton. 2015. Structural complexity enhancement increases fungi diversity in northern hardwood forests. Fungal Ecology 13: 181-192.

Books

Barton, A. and W.S. Keeton (eds.). 2018. Eastern Old-growth Forests: Ecology and Recovery in a Changing World. Island Press, Washington, D.C. In Press.

Book chapters:

Keeton, W.S., C. G. Lorimer, B.J. Palik, and F. Doyon. 2018. Silviculture for old-growth in the context of global change. In: A. Barton and W.S. Keeton (eds.). Eastern Old-growth Forests: Ecology and Recovery in a Changing World. Island Press, Washington, D.C.

Keeton, W.S. 2018. Source or sink? Carbon dynamics in old-growth forests and their role in climate change mitigation. In: A. Barton and W.S. Keeton (eds.). Eastern Old-growth Forests: Ecology and Recovery in a Changing World. Island Press, Washington, D.C.

List of products (Con't.)

Masters Theses:

Gottesman, A. 2016. Tree regeneration dynamics and controls in response to structural complexity enhancement.

Ford, S. 2015. Carbon dynamics associated with structural complexity enhancement in northern hardwood forests.

Undergraduate Honors Thesis:

Dove, N. 2014. Structural complexity enhancement increases fungi diversity in northern hardwood forests.

Presentations:

Invited:

- Keeton, W.S. Structural Complexity Enhancement in northern hardwood forests. North American Forest Ecology Workshop. Edmondton, Alberta, June 2017.
- Keeton, W.S. A North American perspective on disturbance-based forest management. Hungarian Academy of Sciences, Centre for Ecological Research. Budapest, Hungary, March 16, 2017.
- Keeton, W.S. Management for old-growth characteristics and late-successional biodiversity in temperate montane forests. Hungarian Academy of Sciences, Centre for Ecological Research. Budapest, Hungary, March 16, 2017.
- Keeton, W.S. Forest carbon management in the U.S. Northeast. Northeastern Ecosystem Research Cooperative Conference. Saratoga Springs, March 29, 2017.
- Keeton, W.S., Garrett Meigs, Sabina Burrascano, Yurij Bihun, Carlo Blasi, Jiquan Chen, Mykola Chernyavskyy, Dmytro Karabchuk, Brigitte Commarmot, Jerry F. Franklin, Georg Gratzer, Thomas Spies, Mark E. Swanson, Grant Wardell-Johnson, Christopher Dean, Miroslav Svoboda, Volodymyr Trotsiuk, Magdalena Main-Knorn, Christine Goodale, Gregory McGee, Jonathon Thompson, Andrew Whitman. Carpathian Old-growth Forests in a Global Context: Shared Form and Function or Regional Distinctiveness? Keynote Presentation at the Forum Carpaticum. Bucharest, Romania, Sept 28-30, 2016.
- Keeton, W.S. Importance of global old-growth forest conservation. Invited presentation to the Carpathian Convention Secretariat and Working Group on Forests. Brasov, Romania, Sept. 26, 2016.
- Keeton, W.S. G. Meigs et al. Sabina Burrascano, Yurij Bihun, Carlo Blasi, Jiquan Chen, Mykola Chernyavskyy, Dmytro Karabchuk, Brigitte Commarmot, Jerry F. Franklin, Georg Gratzer, Thomas Spies, Mark E. Swanson, Grant Wardell-Johnson, Christopher Dean, Miroslav Svoboda, Volodymyr Trotsiuk, Magdalena Main-Knorn, Christine Goodale, Gregory McGee, Jonathon Thompson, Andrew Whitman. A global analysis of temperate old-growth forests: Universal Ecosystem Services and Conservation Imperative. Invited seminar at Eötvös Loránd University. Budapest, Hungary. March 10, 2016.

List of products (Con't.)

Presentations:

Invited (Continued):

- Keeton, W.S. G. Meigs, Sabina Burrascano, Yurij Bihun, Carlo Blasi, Jiquan Chen, Mykola Chernyavskyy, Dmytro Karabchuk, Brigitte Commarmot, Jerry F. Franklin, Georg Gratzer, Thomas Spies, Mark E. Swanson, Grant Wardell-Johnson, Christopher Dean, Miroslav Svoboda, Volodymyr Trotsiuk, Magdalena Main-Knorn, Christine Goodale, Gregory McGee, Jonathon Thompson, Andrew Whitman. A global analysis of temperate old-growth forests. Invited seminar for the Gund Institute for Ecological Economics. Burlington, VT, Feb 19, 2016.
- Keeton, W.S. Opportunities for carbon market participation in the U.S. Northeast. Annual Meeting of COVERTS. Randolph, Vermont. October 10, 2016.
- Keeton, W.S. Management for old-growth characteristics and late-successional biodiversity in temperate montane forests. Vermont Monitoring Cooperative Annual Meeting. Burlington, VT, December 11, 2015.
- Keeton, W.S. Management for old-growth characteristics and late-successional biodiversity in temperate montane forests. Mountains of our Future Earth. Perth, Scotland, UK October 4-8, 2015.
- Keeton, W.S. Broadening the options for sustainable forestry: emulating natural disturbances and managing for old-growth characteristics. Wood at Work. Bronx Zoo – Wildlife Conservation International, New York, NY. Oct 30, 2015.
- Keeton, W.S. Opportunities for forest carbon projects in Vermont. Invited testimony to the Vermont State Legislature, House Committee on Natural Resources and Energy. Montpelier, VT, April 30, 2015.
- Keeton, W.S. Managing northeastern forests for flood resilience in the face of climate change. Invited speaker, New England Society of American Forests annual conference. Fairlee, VT, March 24-27, 2015.
- Keeton, W.S. We can make forest carbon projects work in Vermont. Invited presentation to the Vermont Forest Roundtable. Randolph, VT, Dec. 18, 2014.
- Keeton, W.S. Keeton, W.S. We can make forest carbon projects can work in Vermont! Gund Research Slam. Gund Institute for Ecological Economics, Burlington, Vermont. Nov. 20, 2014.
- Keeton, W.S., J.R. Nunery, E. Russell-Roy, and C.D. Kerchner. Exploring the potential for forest carbon management in northeastern forests: a research synthesis. Invited presentation. Vermont Agency of Natural Resources, Northeastern States Research Cooperative speaker series. Montpelier, VT, May 15, 2014.
- Keeton, W.S. Forestry practices for climate change adaptation in northern hardwood forests. Invited speaker. Forest Guild National Meeting. Burlington, VT. June 19, 2014.

List of products (Con't.)

Presentations:

Contributed:

- Gottesman, A.J. and W.S. Keeton. Regeneration responses to management for old-growth characteristics in northern hardwood-conifer forests. Ecological Society of American Annual Conference. Ft. Lauderdale, FL. August 11, 2016.
- Gottesman, A.J. and W.S. Keeton. Regeneration responses to management for old-growth characteristics in northern hardwood-conifer forests. Eastern Canada and United States Forest Science Conference (ECANUSA). Burlington, Vt. Sept. 30, 2016.
- Keeton, W.S. and A.J. Gottesman, A.J. Regeneration responses to management for old-growth characteristics in northern hardwood-conifer forests. Vermont Monitoring Cooperative 2016 Conference. Burlington, VT. Dec. 2, 2016.
- Ford, S.E. and W.S. Keeton. Managing northern hardwood forests for carbon storage through Structural Complexity Enhancement: effects on aboveground carbon pools. Ecological Society of America annual conference, Baltimore, MD. Aug. 9-14, 2015
- Keeton, W.S. Experimental gaps and biodiversity responses in the Vermont Forest Ecosystem Management Demonstration Project. Vermont Monitoring Cooperative Conference. December 11, 2014, Burlington, VT.
- Keeton, W.S. Opportunities for northeastern landowner participation in carbon markets. Vermont Legislative Summit. November 18, 2014.

Leveraged Grants:

Trust for Mutual Understanding, 2017-2020. Promoting Close-to-Nature-Silviculture in Hungary and Czech Republic to Achieve Ecosystem Service Benefits: a Tri-lateral Exchange of Ideas and Experience. W.S. Keeton (P.I.). Co-P.I.s: T. Standovar, R. Aszalos, L. Gálhidy, M. Svoboda, M. Mikola´sˇ. $20,00.

High Meadows Foundation and Vermont Housing and Conservation Board. 2017-2018. Vermont Forest Carbon Feasibility and Demonstration Project. W.S. Keeton (P.I.), Co-P.I.: N. Richardson (Vermont Land Trust). $50,000 total ($25,000 to UVM).

USDA McIntire-Stennis Forest Research Program. 2014-2019. Managing the matrix: a framework for assessing ecosystem services in forested landscapes. W.S. Keeton (P.I.). Co-P.I.s: C. Danks, G. Galford, W. Kuentzel, J. O'Neil-Dunne, T. Ricketts, A. Strong, K. Wallin, D. Wang. $958,000

List of products (Con't.)

Webinars:

VT ANR: https://www.youtube.com/watch?v=Ow_WztLulMI

NSRC https://vimeo.com/110070681

Radio Interviews on National Public Radio:

http://digital.vpr.net/post/mimicking-mother-nature-uvm-scientists-nudge-forests-toward-old-growth-conditions#stream/0

http://www.wbur.org/news/2017/04/26/vermont-old-growth-forests

NPR Here and Now: https://www.uvm.edu/newsstories/news/vermont-researchers-speed-tree-aging-process-create-old-growth

Videos:

https://www.youtube.com/watch?v=k19ZFmL1xto

https://www.youtube.com/watch?v=gnW5MQ_9DXc&list=PL6463E2ECF5C8EADA&index=2

Selected online and magazine articles:

https://www.nrdc.org/stories/forests-just-ones-mother-nature-used-make

https://phys.org/news/2017-04-growth-school-forestry-technique-imitates.html

https://www.sciencedaily.com/releases/2017/04/170406102630.htm

https://www.uvm.edu/newsstories/news/new-forestry-old-growth

http://www.uvm.edu/vq/?Page=news&storyID=24650&category=vq-know

Article in Northern Woodlands, Winter 2018 issue