Effects of Long-Term Forest Recovery Pathways and Management History on Carbon Sequestration and Co-Varying Ecosystem Services

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Marsh-Billings-Rockefeller National Historical Park

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- Understanding long-term biomass dynamics is important for managing forests as carbon sinks and for providing co-benefits such as watershed protection and biodiversity.
- This study investigated how long-term pathways of secondary forest recovery, including different reforestation and management histories, have influenced stand structural development and aboveground carbon storage in the U.S. Northeast.
- The findings suggest that a variety of reforestation and recovery pathways converge on high levels of aboveground carbon storage, but choice of silvicultural management approach can dramatically alter those trajectories.
- Multifunctional forestry has utility for integrating carbon with management for late-successional habitats in northern hardwood, mixed hardwood-conifer, and conifer stands in the northern forest.

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http://www.nsrcforest.org

Project Summary

Temperate forests are an important carbon sink, yet there is uncertainty regarding land-use history effects on biomass accumulation and carbon storage potential in secondary forests. Understanding long-term biomass dynamics is important for managing forests as carbon sinks and for co-benefits such as watershed protection and biodiversity. How have secondary forests of the U.S. Northeast recovered post nineteenth century agricultural abandonment? How has the region's extensive land-use history influenced long-term structural development and aboveground carbon storage? To answer these questions, we employed a longitudinal study based on twelve years of empirical data (2001-2013) from the Marsh-Billings-Rockefeller (MBR) National Historical Park in Woodstock, VT. MBR Park was the first parcel of land to actively be reforested in the eastern U.S., and as such, its diverse forest mosaic reflects a history of alternate reforestation approaches and varied successional trajectories indicative of secondary forest recovery occurring across the broader northeastern forest landscape. We also used 150 years of documentary data from park management records. This research evaluates the effects of reforestation approaches (planting vs. natural regeneration), management regimes (long-term low-to-intermediate harvest intensities at varied harvest frequencies), and stand development pathways on biomass outcomes. We generated biometrics representative of stand structural complexity, including the *H'* structural diversity index, and aboveground biomass (live trees, snags, and downed coarse woody debris pools) estimates. Multivariate analyses evaluated the predictive strength of reforestation approach, management history, and site characteristics relative to aboveground carbon pools and stand structural complexity.

Classification and Regression Tree (CART) analysis ranked reforestation approach (plantation or natural regeneration) as the strongest predictor of long-term mean total aboveground carbon storage, while harvest frequency, and stand age were selected as secondary variables. CART ranked forest percent conifer (a metric closely associated with reforestation approach) as the strongest predictor of *H'* index, while harvest intensity, and harvest frequency were selected as secondary variables. Increases in harvest intensity can significantly reduce aboveground carbon storage. Our results suggest that a variety of long-term recovery pathways converge on high levels of aboveground carbon storage, including both conifer plantations and naturally regenerated hardwood stands, but choice of silvicultural management approach can dramatically alter those trajectories. Importantly, total aboveground biomass (i.e., carbon) co-varied with *H'* index and thus, our dataset showed a positive relationship between forest carbon storage and structural complexity, supporting the utility of multifunctional forestry integrating carbon with management for late-successional habitats.

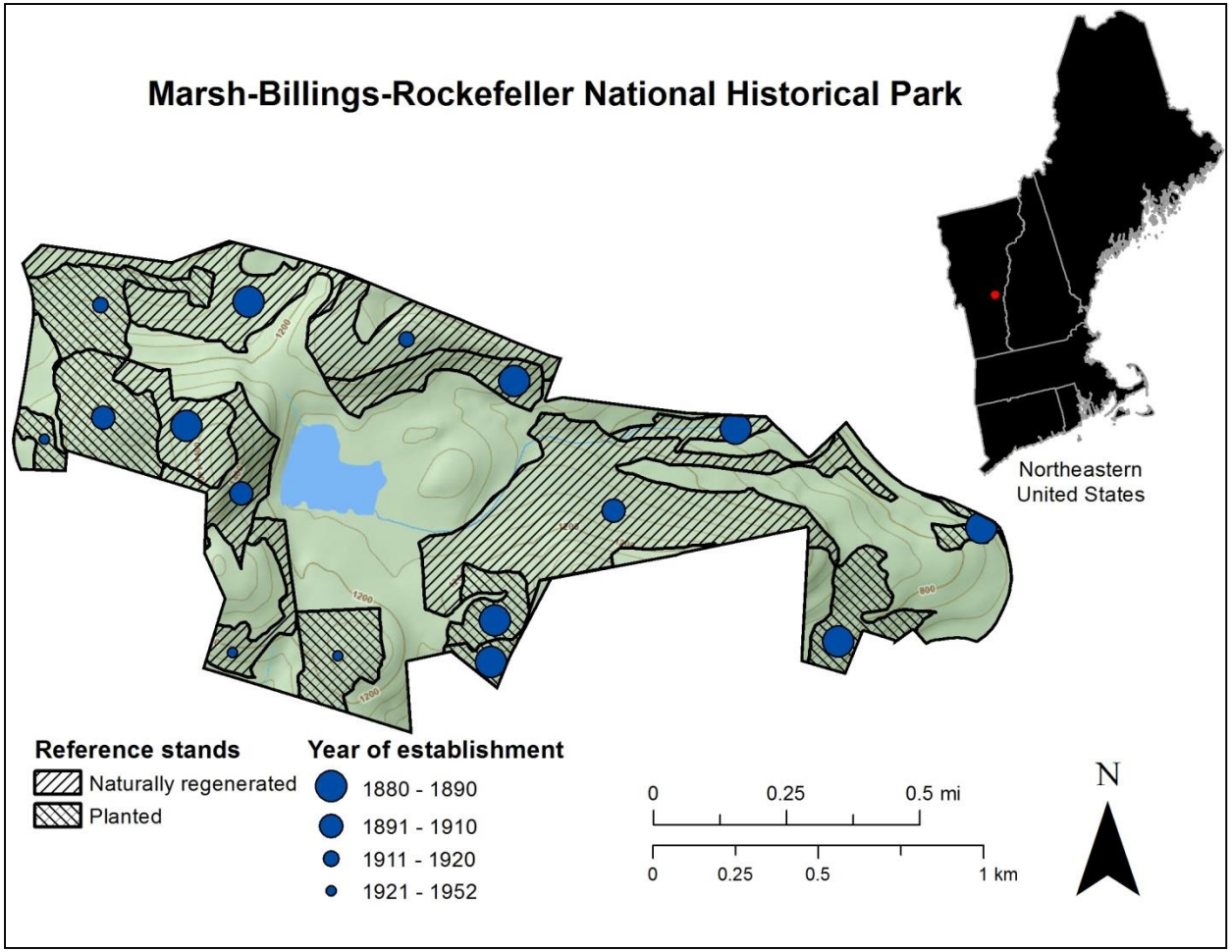
Background and Justification

View of the Marsh-Billings-Rockefeller National Historical Park, Woodstock, VT

Background and Justification

- There is an unprecedented opportunity to study the long-term dynamics of secondary forest recovery from land-use change in the northeastern United States. Following wide spread forest clearing and subsequent agricultural abandonment in the nineteenth century, the region has reverted to a predominance of forest cover, though cover is again declining in all six New England states.
- This land-use history provides an opportunity to reexamine stand development models based largely on theoretical projections and observations spanning a relatively limited range of successional conditions.
- In light of increasing interests in managing forests as carbon sinks and for environmental co-benefits, such as watershed protection and biodiversity, understanding long-term carbon accumulation dynamics is essential.
- Successional dynamics in the northeastern U.S. have been profoundly altered by land-use history, creating multiple potential pathways of compositional and structural development.
- In addition, our understanding of late-successional dynamics (i.e., structural and compositional change) in northeastern forests remains incomplete. Despite recent work on carbon accumulation dynamics in old-growth and primary forests ,and comparisons of forest management scenarios, it remains uncertain whether the region's northern hardwood, conifer, and mixed hardwood-conifer forests are recovering towards a high biomass condition yielding carbon storage and climate change mitigation benefits. This is partly attributable to conflicting reports on the relationship between tree growth rates and biomass carbon accumulation dynamics.
- It is, therefore, unclear if, how, and to what degree the region's forests are recovering towards a high-biomass, late-successional condition, and furthermore if these two characteristics are tightly or consistently correlated. An important and related question pertains to how over a century of forest management has influenced the pathways of forest structural and compositional development.
- We hypothesized that multiple pathways of recovery, management, and stand development are converging on similar high biomass conditions, yielding occurring increases in our considered elements of stand structure..
- The study investigated the influence of (1) different reforestation approaches (i.e. plantation forestry vs. natural recolonization and regeneration) and (2) management history (i.e., long-term low harvest intensities with varying levels of harvest frequencies) on aboveground carbon storage and structural development, and how, if at all, forest management alters these developmental pathways.

Methods



Map of Study Area.

Forest reference stands located in MBR National Historical Park. The stands are differentiated by reforestation approach (naturally regenerated vs. planted). Blue circles represent the date (range) of stand establishment, with larger sizes representing older stand ages.

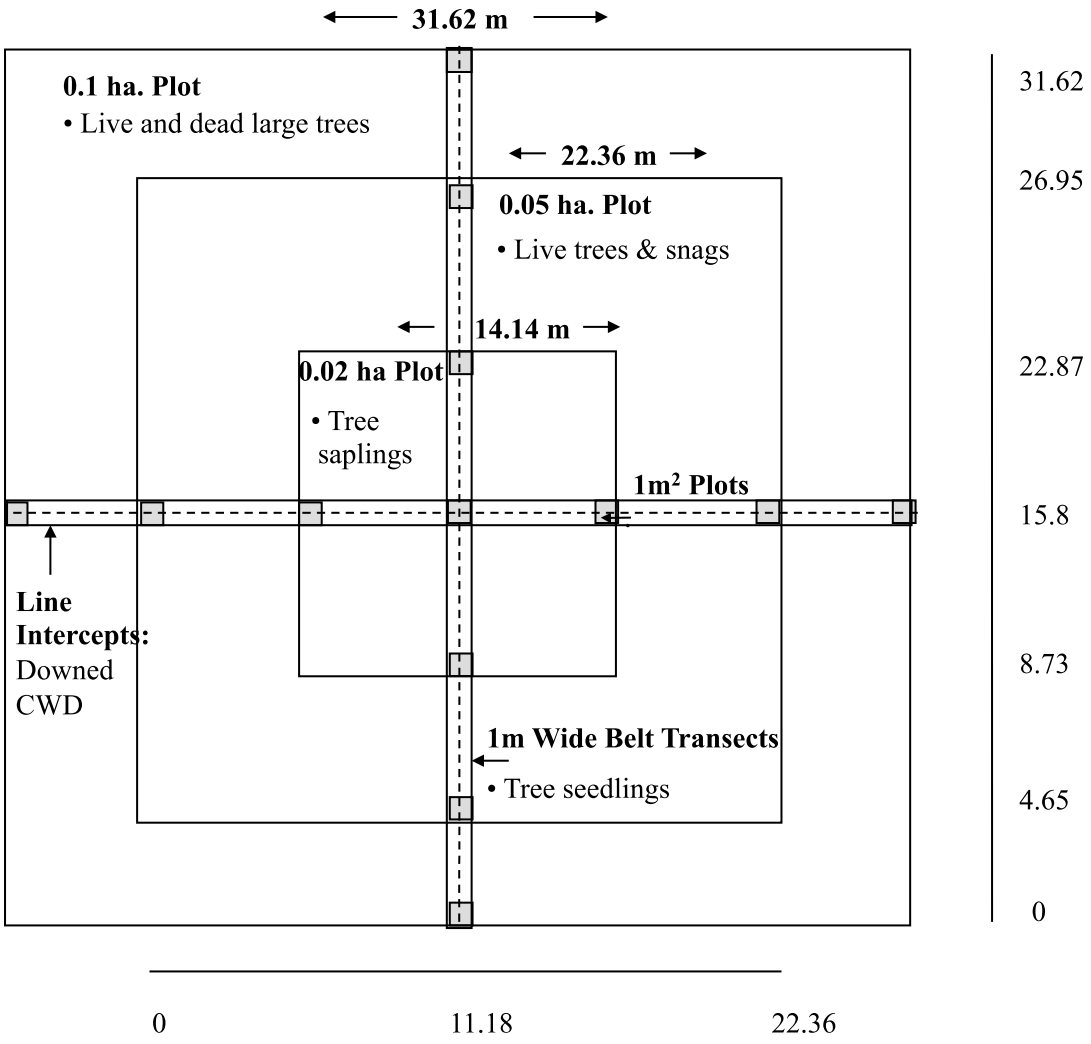
Methods

- We employed a longitudinal study based on twelve years of empirical data (2001-2013) collected from 60 permanent monitoring plots within 16 reference stands at the Marsh-Billings-Rockefeller (MBR) National Historical Park in Woodstock, VT. We also used 150 years of documentary data from park management records.

Picture of one of the permanent monitoring plots established in 2001 at MBR

Methods

Monitoring plot design and inventory protocol for aboveground biomass pools. Sixty fixed 0.05 ha plots were established throughout 16 reference stands in 2001.



Methods

Data Processing and Statistical analyses

- Forest inventory data were input into the Northeast Ecosystem Management Decision Model to generate a variety of forest-structure metrics, including aboveground live tree biomass estimates based on species group-specific allometric equations. Carbon in standing dead carbon and downed coarse woody debris was quantified according to California Air Resources Board carbon inventory protocol.
- Nearly 150 years of documentary data from Park records were used to assess stand management history spanning the time period of 1880 to 2013. These stand narratives provided the following information: the date of stand establishment, method of establishment (i.e., naturally regenerated or planted), and management history (i.e., harvest frequency and intensity).
- Based on the historical documentation, two ordinal rankings (0-5) and categorical classifications (low vs. high), one for harvest intensity and one for harvest frequency, were assigned to each reference stand in both datasets (2003 and 2013).
- A modified version of Shannon-Wiener diversity index, *H'*, was used to quantify structural complexity. The *H'* index describes how basal area is apportioned by species and size class for all plots.
- Relationships between reforestation approach, site characteristics, and management history (predictor variables) and aboveground carbon and structural complexity were examined using Classification and Regression Tree (CART) analysis run in S-Plus software.
- All statistical analyses were conducted twice: once with the 2003 dataset (data spanning from date of stand establishment to the 2003 inventory) and once with the 2013 dataset.
- Analyses using the 2003 dataset were employed to examine stand development pathways characterized by long-term recovery from 19th century land-use. Hereafter we will refer to these as the “long-term recovery” pathway.
- Analyses using the 2013 dataset were indicative of altered trajectories of stand development resulting from elevated harvesting activity between 2004 and 2013, which we hereafter refer to as the “contemporary management” pathway.
- Thus, our 2003 dataset is most indicative of long-term stand recovery dynamics, while our 2013 dataset helps us understand the effects of recent management.

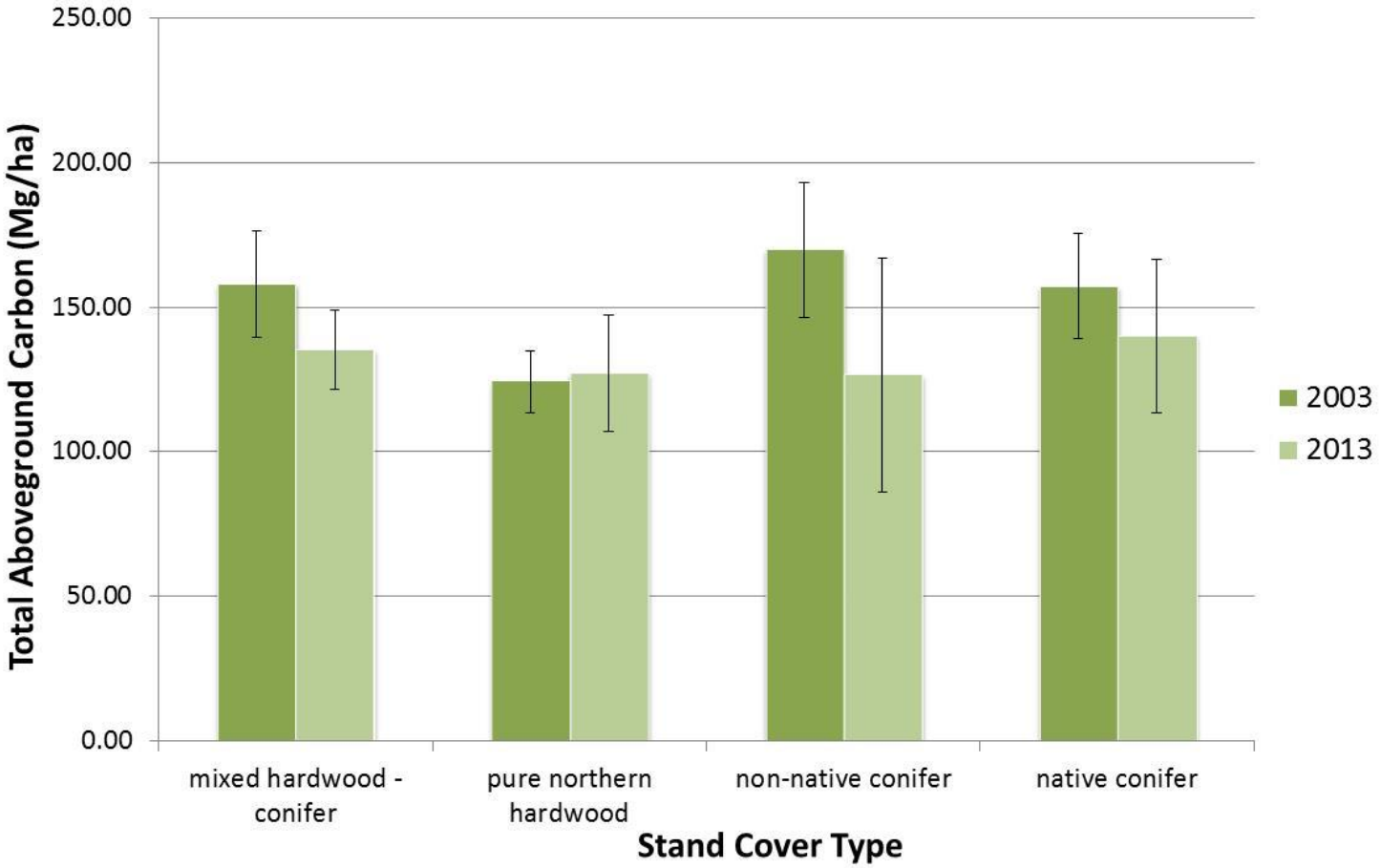
Methods

- Predictor and response variables and variable types employed in statistical analyses. Note that total aboveground carbon is derived from summing the average live, standing dead, and downed CWD (all stages, 1-5).

Predictor variables	Variable type	Response variable	Variable type
Site class	Ordinal	**Structure Pools**	
Stand age (years)	Continuous ratio scale	H' Index	Continuous ratio scale
		Aboveground	
Harvest intensity	Ordinal (0-5), Categorical (low vs. high)	**Carbon Pools (Mg/ha)**	
Harvest frequency	Ordinal (0-5), Categorical (low vs. high)	Total	Continuous ratio scale
Some variation of:		Live	Continuous ratio scale
Reforestation approach (NR or PL)	Categorical	Standing dead	Continuous ratio scale
Cover type	Categorical	Down CWD all stages	Continuous ratio scale
Percent conifer (by composition BA)	Continuous ratio scale	Down CWD stages 3-5	Continuous ratio scale

Results/Project outcomes

- Secondary forests can reach high levels of C storage sooner than previously thought



Error bars are +/- one standard error of the mean

Results/Project outcomes

- CART analyses suggest that forest management history had the greatest predictive strength for long-term carbon storage in all (live and dead) aboveground biomass pools.
- CART ranked forest cover type as the strongest predictor of H' index, while harvest intensity, harvest frequency, and site class were selected as secondary variables.

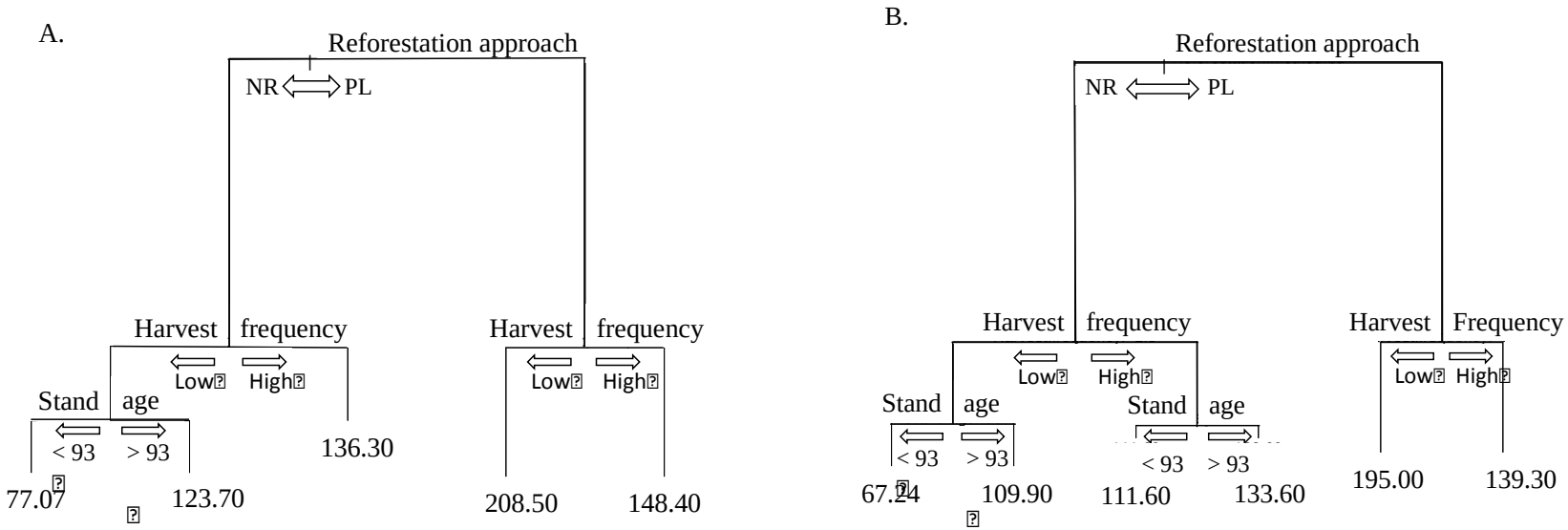


Figure explanation: CART model, showing statistically significant predictor variables selected, split values, and partitioned mean values (bottom) of the response variable (A. mean total aboveground carbon, B. mean live tree aboveground carbon, *n* = 16). The figure ranks variables by predictive strength (top to bottom) and in sequential order of importance as the response variable increases (left to right). Stands with low harvest frequencies received an ordinal classification of ≤ 2. Stands with high harvest frequencies received an ordinal classification of ≥ 3. Stand age is in years. The length of each vertical line is proportional to the amount of deviance explained. Predictor variables were selected from an initial set of 6 variables.

Results/Project outcomes

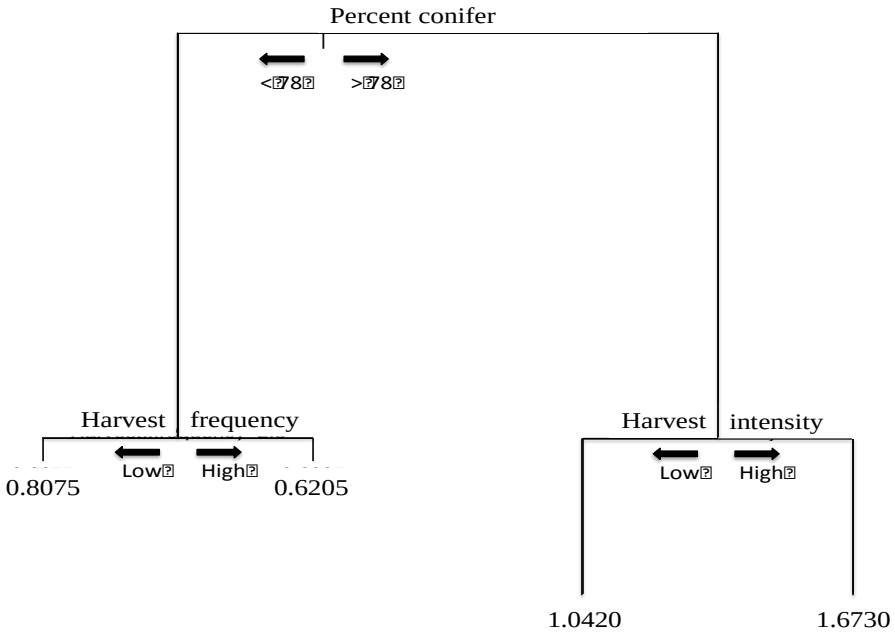


Figure explanation: CART model, showing statistically significant predictor variables selected, split values, and partitioned mean values (bottom) of the response variable (mean H' structural diversity index, n = 16). The figure ranks variables by predictive strength (top to bottom) and in sequential order of importance as H' increases (left to right). Stands with low harvest frequency or intensity received an ordinal classification of ≤ 2. Stands with high harvest frequency or intensity received an ordinal classification of ≥ 3. The length of each vertical line is proportional to the amount of deviance explained. Predictor variables were selected from an initial set of 6 variables.

Results/Project outcomes

- There are positive relationships between stand age, structural complexity, and carbon storage
- Carbon and stand structural complexity co-vary

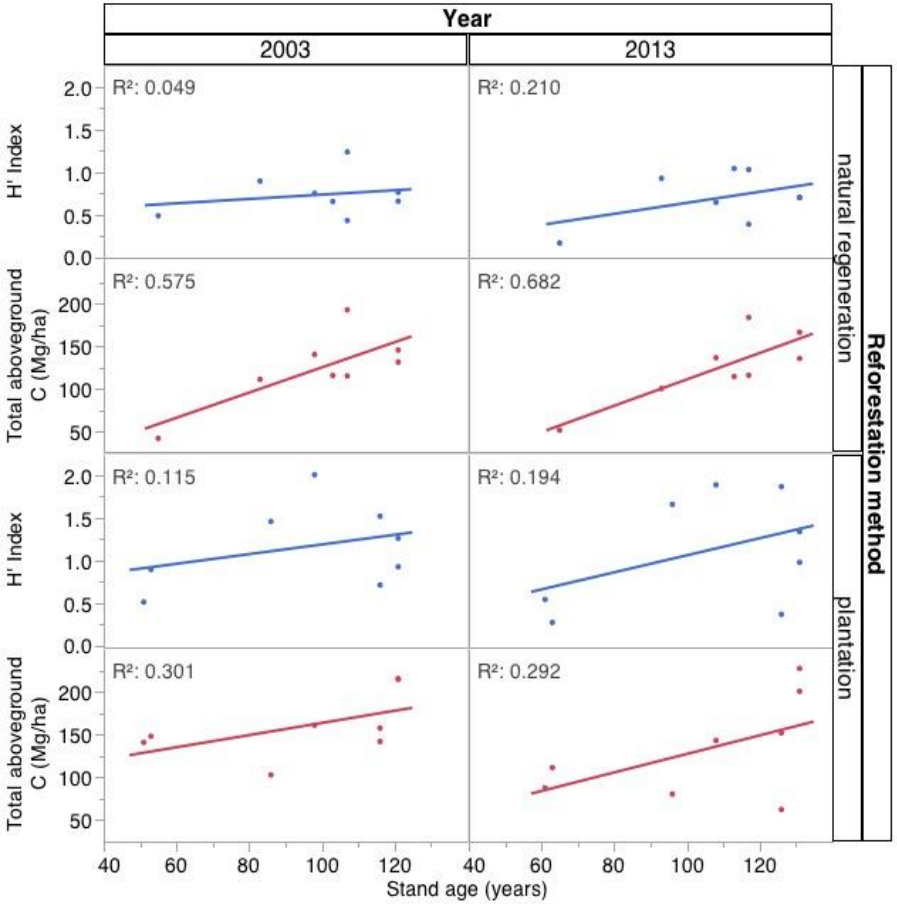


Figure explanation: Mean total aboveground carbon (Mg/ha) and H' structural diversity index over time (age), by reforestation approach and year.

Implications and applications in the Northern Forest region

- Recovering secondary northeastern forests play a vital role in carbon sequestration and thus are helping to mitigate or dampen the future intensity of climate change.
- The high carbon storage observed in MBR's mature, planted and naturally regenerated stands supports previous reports that aboveground biomass can accumulate late into stand development in secondary forests
- The recovery that occurred to 2003 suggests the high potential for carbon accumulation on sustainably managed landscapes, particularly where an emphasis is placed on maintaining high stocking.
- Secondary forests have potential to re-achieve high level of C storage as reported previously in primary forests.
- High-magnitude C storage can occur prior to reaching old-growth age.
- There is a positive relationship between stand age and C.
- Aboveground C storage and stand structural complexity are often, but not always, positively correlated.
- More intensive silvicultural treatments can alter recovery trajectories.

Implications and applications in the Northern Forest region

Options for enhancing carbon storage and related late-successional structural co-benefits in secondary forests include:

- Reducing harvest frequency
- Increasing rotation lengths or entry cycles
- Increasing post-harvest structural retention
  - Biological legacies
  - Downed woody debris
  - Large trees
- There is a carbon storage role for mature plantations of native conifers. These store high levels of carbon, though have lower stand structural complexity.
- Reserve-based approaches emphasizing carbon storage through forest maturation
- Integration of carbon forestry with other management objectives across multiple stands in working forests

By managing forests for high carbon storage, we are likely to provide late-successional habitats important for under-represented elements of biological diversity

Future directions

- Research on silvicultural approaches integrating carbon, late-successional biodiversity, and riparian functions such as flood resilience

- Research on landscape-scale implications of altered disturbance regimes for carbon storage related to forest maturation

List of products

Peer-reviewed publications:

Urbano, A.R. and W.S. Keeton. Long-term forest structural development and carbon dynamics as influenced by land-use history and reforestation approach. Ecological Applications. (to be submitted December 2015).

Mikoláš, M. M. Svoboda, V. Pouska, R. C. Morrissey, D. C. Donato, W. S. Keeton, T. Nagel, V. D. Popescu, J. Müller, C. Bässler, J. Knorn, L. Rozylowicz, M. C. Enescu, V. Trotsiuk, P. Janda, H. Mrhalová, Z. Michalová, F. Krumm, and D. Kraus. 2014. Comment on the "Opinion paper: Forest management and biodiversity": The role of protected areas is greater than the sum of its number of species. Web Ecology 14:61–64.

Burrascano, S., W.S. Keeton, F.M. Sabatini, and C. Blasi. 2013. Commonality and variability in the structural attributes of moist temperate old-growth forests: A global review. Forest Ecology and Management 291:458–479.

Graduate theses:

Urbano, A.R. 2015. Long-term forest structural development and carbon dynamics as influenced by land-use history and reforestation approach. Masters Thesis. University of Vermont, Burlington, VT. 103 pp.

Abstracts:

Urbano, A.R. and W.S. Keeton. 2015. Long-term forest carbon storage and structural development as influenced by land-use history. Ecological Society of America annual meeting. August 2015, Baltimore, MD. Available at http://eco.confex.com/eco/2015/webprogram/Paper54400.html

Leveraged grants:

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

USDA Forest Service McIntire-Stennis Forest Research Program. 2012-2015. Reactivation of the Vermont Forest Ecosystem Management Demonstration Project. W.S. Keeton (P.I.). $75,000.

List of products (Cont.)

Presentations:

Urbano, A.R. and W.S. Keeton. 2015. Long-term forest carbon storage and structural development as influenced by land-use history. Ecological Society of America annual meeting. August 13, 2015, Baltimore, MD.

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. We can make forest carbon projects work in Vermont. Invited presentation to the Vermont Forest Roundtable. Randolph, VT, Dec. 18, 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 speakers series. Montpelier, VT, May 15, 2014.

Keeton, W.S. Toward a unified vision of forest carbon management. Invited Keynote. International Scientific Conference on Earth Bioresources and Environmental Biosafety: Challenges and Opportunities. Kiev, Ukraine. Nov. 4-7, 2013.

Keeton, W.S., D. Foster et al. (18 co-authors). Wildlands and woodlands: A vision for the New England landscape based on investigations of long-term land-use change. Invited Keynote. Forest cover changes in mountainous regions: drivers, trajectories and implications, Opening Conference. Jagiellonian University, Krakow, Poland, March 8, 2013.

Keeton, W.S.. Cross-regional perspectives on ecosystem management in temperate forest systems. Invited plenary presentation. 92nd Congress of Quebec Forest Engineers, Gatineau, Quebec, Canada. Sept. 11, 2013.

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. New England Society of American Forests Annual Conference, Saratoga Springs, NY. Jan. 31, 2013.