Managing an Aging Resource: Influence of age on leaf area index, stemwood growth, growth efficiency, and carbon sequestration of eastern white pine

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Leaf area index of fully stocked eastern white pine stands peaks early in stand development (height = 12 m, age 15-20) at values of 6-7 m^2/m^2 (projected), then declines to an asymptotic value of ca. 4 at a height of 20-25 m. Site index and relative density influence LAI positively at a given height. Stemwood productivity and growth efficiency peak similarly but decline more gradually. Old pine stands continue to accumulate stemwood biomass and carbon to at least age 210; our oldest plot has nearly 1,200 m^3 per ha of stemwood, sequesters 235 metric tons per ha of stemwood carbon, and is still growing nearly 12 m^3 per ha per year.

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http://www.nsrcforest.org

Project Summary (1)

The white pine resource of New England, once dominated by sapling and pole-sized stands of old-field origin, has matured, and is now largely in sawtimber-sized stands. Despite a voluminous literature on pine silviculture and pest management, few studies have quantified the biological productivity of older (> age 100) pine trees and stands, nor are there any studies of very young stands not yet merchantable. To address these deficiencies, over 25 years ago PI Robert Seymour began a comprehensive, long-term study of the production ecology of eastern white pine on which this study is centered. One set of permanent plots addresses the issue of appropriate commercial thinning prescriptions in middle-aged stands, comparing conventional B-line thinning against low-density prescriptions and unmanaged controls. This study was supported by an earlier NSRC Grant in 2007; 17-year findings have been published (Guiterman et al. 2011, Guiterman et al. 2012) and monitoring continues. A second set of plots addresses the fundamental biological question of how forest productivity changes as trees and stands age; this study includes white pine monocultures over a chronosequence that range from age 5 (at breast height) to over 200. Both studies monitor stand leaf area index (LAI) by uninterrupted semi-annual litterfall collections, combined with repeated tree measurements on permanent plots from which growth is determined.

Project Summary (2)

- A new density management diagram (DMD) was developed from these data, which has a significantly flatter slope of the maximum density line compared to previously published DMDs. This will allow foresters to improve thinning and shelterwood prescriptions, and to quantify yields from thinning treatments. LAI development is modeled with a flexible double-logistic function (Ogawa 2012) which peaks at values of 6-7 (depending on site index) at heights of 12-15 m depending on early treatment, then declines to an apparent asymptote of about 4 at heights of 25 m. Productivity is commensurately high in very young stands, with annual stemwood growth rates over 20 m^3 ha^{-1} on very dense young plots; these values exceed any in the published literature for northeastern species. Productivity of fully stocked stands then declines gradually to about 10 m^3 ha^{-1} at age 70-80, after which it stabilizes similar to LAI. Stemwood growth efficiency also declines, but more slowly. The oldest plot, over age 200, continues to grow very well, at 12 m^3 ha per year of stemwood volume and 7.5 metric tons per ha of carbon dioxide equivalent. This stand has accumulated nearly 1,200 m^3 ha^{-1} of stemwood volume and 235 tons ha^{-1} of stemwood carbon; this is nearly five times the "common practice" level established by the California Air Resources Board for this forest type and region based on FIA data, a remarkable statistic by any standard. Regression equations are presented that predict stemwood volume, oven-dry mass, stemwood carbon, and carbon dioxide equivalent, as a function of stand age, relative density, and site index.

Background and Justification

- The white pine resource of New England is rapidly maturing and is overwhelmingly dominated by mature stands, with over 80% of the resource in the sawtimber size class (McWilliams et al 2005).
- Should these aging stands be regenerated as rapidly as possible, as traditional timber management theory might suggest, or can they be carried on much longer rotations, maintain excellent growth rates, and continue to sequester large quantities of carbon?
- Answering this question requires a detailed understanding of the production ecology of eastern white pine over a complete range of ages (a so-called "chronosequence"), from newly regenerated sapling stands to the old-growth stage of 200 years and beyond.
- Virtually all such chronosequence studies demonstrate that above-ground net primary productivity declines after reaching a peak, following a similar trend in stand leaf area index (LAI; Ryan et al 1997).

Background and Justification

- For many species, growth efficiency (GE, biomass produced per unit of leaf area) also begins to decline fairly rapidly at about the same point in stand development (Martin and Jokela 2004; Ryan et al 2004, Pregitzer and Euskirchen 2004), whereas other species do not show such a decline until much later (exceptions in Ryan et al 1997, their Fig. 3; O'Hara 1996).
- Preliminary analysis (unpublished) of long-term tree and plot data maintained by the Principal Investigator suggest that white pine falls in this latter category, with LAI peaking quite early (ca. age 20, as also found by Peichl and Arain 2006) but with growth and GE peaking much later, if at all.
- Such a pattern offers the possibility of growing pine on extended rotations without sacrificing forest productivity.
- Growing evidence suggests that extended rotations in such forest types also offer substantial benefits in regional carbon sequestration (Nunery and Keeton 2010; Hennigar et al 2008; Luyssaert et al. 2008; Ryan et al. 2011).

Objectives

The main goal of this study is to quantify the key attributes of the production ecology of eastern white pine over a 200+-year chronosequence, for the purpose of formulating optimal rotations and regeneration strategies for the maturing pine resource of New England. Specifically:

- Quantify the effects of age and stand density on leaf area index (LAI), following the models of Long and Smith (1992) and DeRose and Seymour (2010).
- Quantify the stemwood and total above-ground productivity (biomass, carbon) and growth efficiency over this same chronosequence.
- Compare the patterns documented to those predicted by the Fire and Fuels Extension of the Forest Vegetation Simulator (Dixon 2001).

Methods

- The data analyzed here come from a long-term study on the University of Maine's Demeritt Forest, and fall into two basic categories: (1) naturally regenerated plots with no known history of density management and high relative densities (> 0.7) ranging in age (at breast height) from 5 to 203 years, hereafter called the "Chronosequence Study"; and (2) young (5-10) and middle-aged (40) stands subjected to various thinning treatments (the "Thinning Study").
- Leaf area index (LAI) is estimated from uninterrupted semi-annual litterfall collections over periods ranging from 4 to 23 years.
- Forest stand data come from remeasured permanent fixed-area plots of 0.01 or 0.04 hectares in area depending on stand age.
- Litterfall data is collected in 0.5-m square (0.25 m^2 area) traps near the forest floor, typically with 5 traps per plot. In the thinning study, 6 plots (30 traps) have been sampled continuously since 1992; 5 plots (25 traps) were added in the control plots in 2001, and 5 more thinned plots (25 traps) were added in 2007. Collection of these 75 traps is ongoing. A 17-year record of these collections was published in 2012 (Guiterman et al 2012).

Methods (continued)

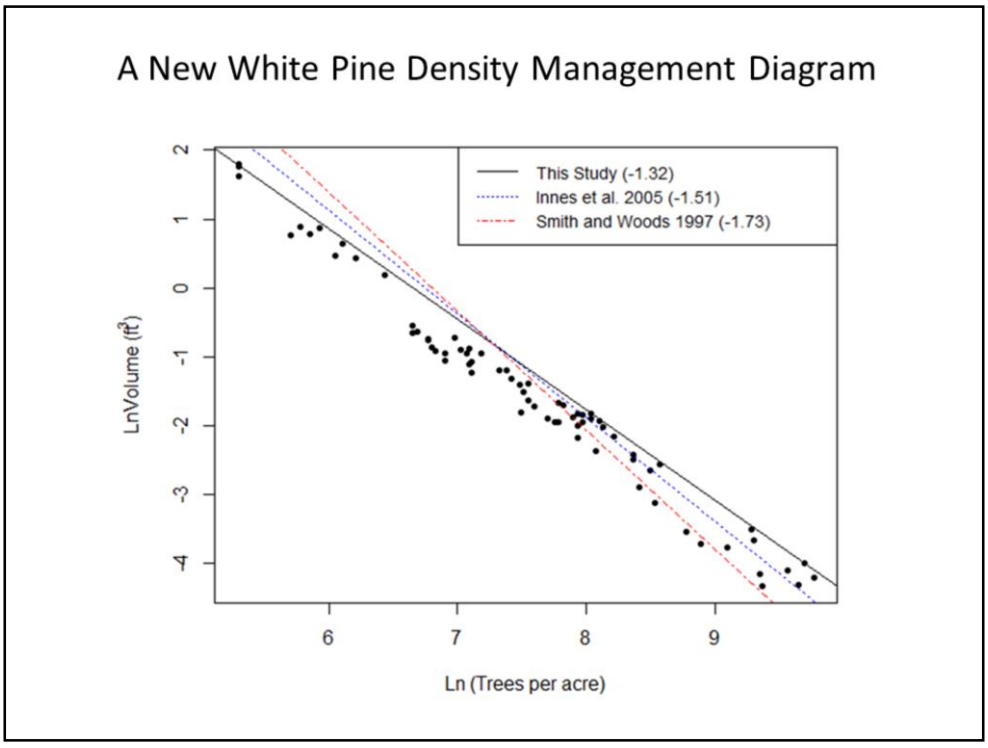
- The chronosequence plots were established over time. Six traps on three 0.01-ha plots were installed in an extremely dense (5000 trees per ha) plantation in 1992 adjacent to the thinning study; this was followed by another dense young stand in 1996 (4 traps), then by 3 young precommercially thinned plots in 1998 (12 traps). Other traps were added in 2002 (n=5, an old-growth stand), 2004 (n=6, very young saplings), and 2010 (10 traps on two plots ages 85 and 110). Two plots with 8 traps were also monitored from 1992-2001 in a dense old-field stand originating ca. 1955.
- Litter Traps are collected twice a year, first in late October immediately after the majority of the needle-fall, then again in late May to collect remaining material that fell over winter. Litter is oven-dried at 60 degrees C to a constant weight, sorted into components (needles, woody material, seeds and cones) and weighed.
- Needle mass data are converted to projected (one-sided), fresh surface areas using a specific leaf area of 65.25 cm^2 per gram, based on hundreds of measurements of frozen green needles from destructively sampled trees of all sizes on a high-resolution backlit scanner using the WinSeedle software package from Regent Instruments. These data are multiplied by a correction factor of 1.151, which adjusts for dry-matter loss during needle senescence. Annual litterfall is converted to canopy LAI assuming needle retention of 2.2 years, based on samples of 60 shoots measured in August at the peak seasonal leaf area.

Methods (continued)

- Plots have been measured approximately every 5 years, sometimes more frequently. All trees are numbered with marked dbh-measurement points. Dbh is measured with a tape to the nearest mm; heights of trees over about 8 m tall are measured on all trees to the nearest 0.1 m with a Haglof Vertex. Shorter trees are measured with a telescoping pole to the nearest cm. Stemwood volumes are calculated using Honer's (1967) equation form, as refitted by Li et al. (2012).
- Stemwood biomass (oven-dry) was calculated using the ratio of 415 kg per cubic meter for *Pinus strobus* compiled in Table 1B of Miles and Smith (2009).
- Stemwood carbon was calculated from biomass assuming white pine wood is 49.74% carbon (Lamlom and Savidge 2003).
- Stand top height is defined as the average of the tallest 100 trees per hectare.
- Site index was calculated as the top height of the plots at a total age of 50, using the base-age-50 equation in Parreson and Vissage (1998). For natural stands, total age was determined by adding 8-10 years to the breast height age depending on site index. For the thinning study (a plantation) total age was the time since planting plus two years (the seedling age when planted).

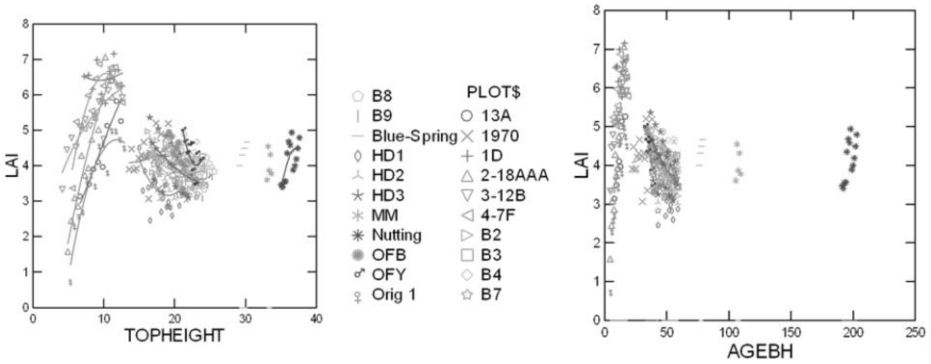
Methods (continued)

- Summaries of these data, undertaken with Microsoft Access and Excel, yield two different datasets. The first dataset includes 481 observations of annual litterfall linked to stand metrics that can be calculated (age, site index) or reliably interpolated (height) between 5-year plot measurements. The second dataset of 92 observations links stand metrics and annual growth rates to litterfall-based LAIs.
- For these latter growth data, LAI is calculated as the annual average over the growth period plus one year following (if available), as the best estimate of the leaf area actually contributing the observed stemwood growth. Unless stated otherwise, "growth" is gross growth, calculated as the difference in standing volumes between the beginning and end of the period, adding back the volume of mortality based on the dead trees' dimensions at the beginning of the period. No dbh thresholds are used; all data include any tree with a measurable dbh.
- Stemwood growth efficiency was calculated as the ratio of stemwood produced per hectare (volume in m^3, biomass in Mg) per hectare of leaf area (i.e., the LAI).
- Although all plots are within 3 km of each other, soils include series from three different catenas. The thinning study and old-growth stands are growing on moderately well-drained, fine-textured marine sediments (clays) of the Buxton series. The 1990 and 3x3 PCT plots are mapped as glacio-fluvial deposits (outwash sands) of the Colton (well drained) and Atherton (moderately well drained) series. The remaining plots are growing on moderately well drained glacial tills (stony silt-loams) of the Thorndike and Plaisted series.



Comparison of maximum density lines constructed for eastern white pine in Ontario and New Hampshire and this study. This study has a significantly "flatter" maximum density line, owing to a more extensive dataset at both ends of the data. The equation is : Log = 4.83978-1.3173*LogTPA; the coefficient -1.3173 is significantly different than the theoretical value of -1.5.

LAI Patters over Height and Age



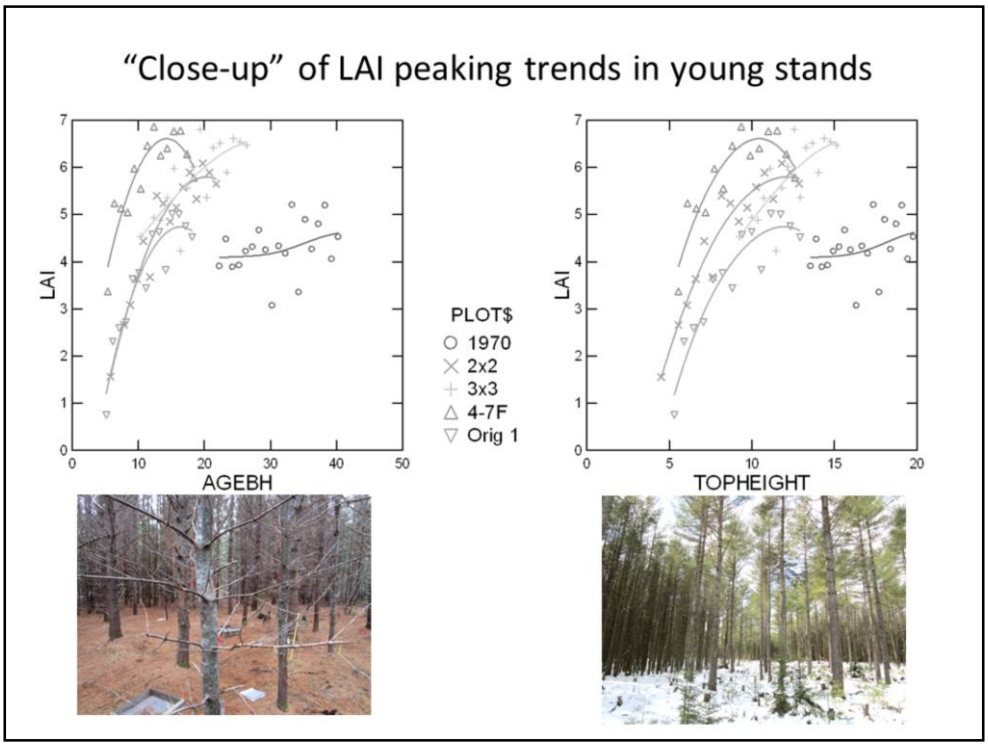
LAI = (RELDENS^A3)*(A1*SI_M^A2)*(B2/(1+.0008*EXP(B4*(TOPHEIGHT))) + 3000)*(C2/(1+C3*EXP(-C4*(TOPHEIGHT))))

Parameter Estimates

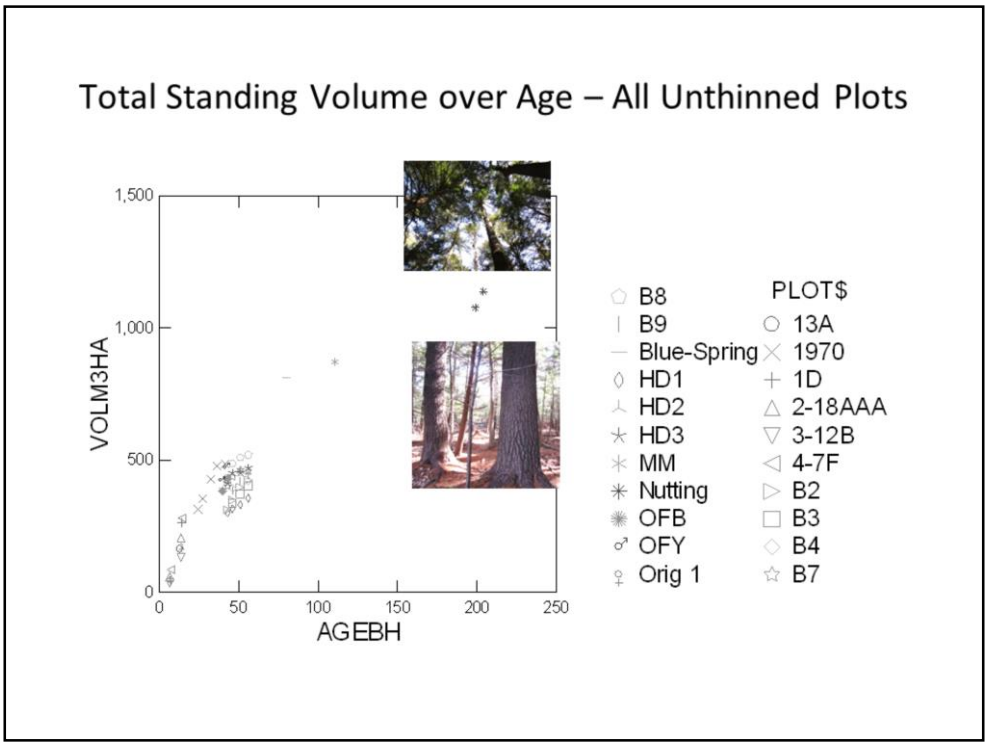
Parameter	Estimate	ASE	Parameter/ASE	Wald 95% Confidence Interval Lower	Upper
A3	0.228599	0.038726	5.903008	0.151602	0.305597
A1	0.017737	0.024930	0.711503	-0.031829	0.067304
A2	1.384527	0.464788	2.978834	0.460403	2.308651
B2	3,780.999777	1,894.999239	1.995251	13.233469	7,548.766086
B4	0.473218	0.032478	14.570435	0.408643	0.537793
C2	0.001300	0.000000	.	.	.
C3	4.322383	2.146374	2.013807	0.054817	8.589949
C4	0.177731	0.067088	2.649239	0.044343	0.311119

TOPHEIGHT is height of 100 tallest trees per ha (meters)
RELDENS = relative density, from DMD above
SI_M = site index (meter) at total age 50
R^2 = .67

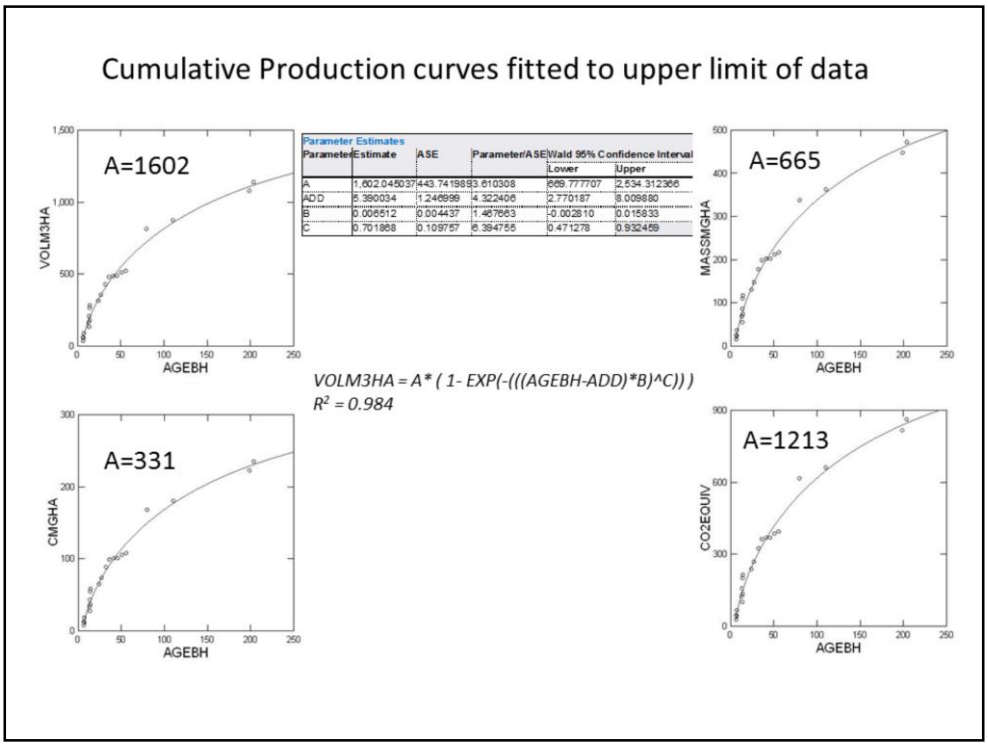
Over a chronosequence of long-term plots, Leaf Area Index (LAI) of eastern white pine rises rapidly to an apparent peak at a height of ca. 12-13 m (breast height age 15-18), then gradually declines or reaches a plateau at about 25-30 meters (bh ages 80-110). Both site index and relative density influence the level of this curve, in a non-linear fashion. The best model was a double-logistic equation (Ogawa 2012); parameters fit with nonlinear regression are shown in the table. Note that the 200-year old-growth plot has as much LAI as 50-year-old stands.



Actual LAI trajectories of 5 dense, young stands; trends highlighted with a LOWESS smoother. Interestingly the precommercially thinned stands 2x2 (left photo) and 3x3 appear to reach the peak LAI several meters in height later than stands with no history of density reduction or spacing. Right photo, dense stand on left, is the 1970 stand in 2016, in contrast to the low-density (LD) thinning on right.



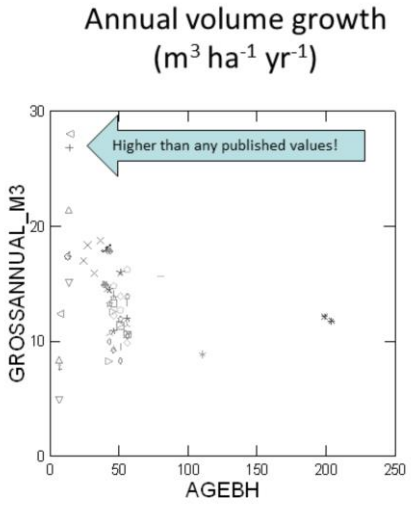
Scatter plot of total stemwood volume, all unthinned plots.



Parameter Estimates

Parameter	Estimate	ASE	Parameter/ASE	Wald 95% Confidence Interval	
				Lower	Upper
A	1,602.045037	443.741989	3.610308	669.777707	2,534.312366
ADD	5.390034	1.246999	4.322406	2.770187	8.009880
B	0.006512	0.004437	1.467663	-0.002810	0.015833
C	0.701868	0.109757	6.394755	0.471278	0.932459

Equations (Weibull distribution functions) to predict maximum production of eastern white pine as a function of age alone. VOLM3HA = cubic meters of stemwood volume per ha; MASSMGHA = metric tons of oven-dry stemwood biomass per ha; CMGHA=metric tons of stemwood carbon per ha; CO2EQUIV= metric tons of carbon dioxide equivalent to CMGHA. All parameters are identical except A, the asymptotic upper limit implied by the equation form.

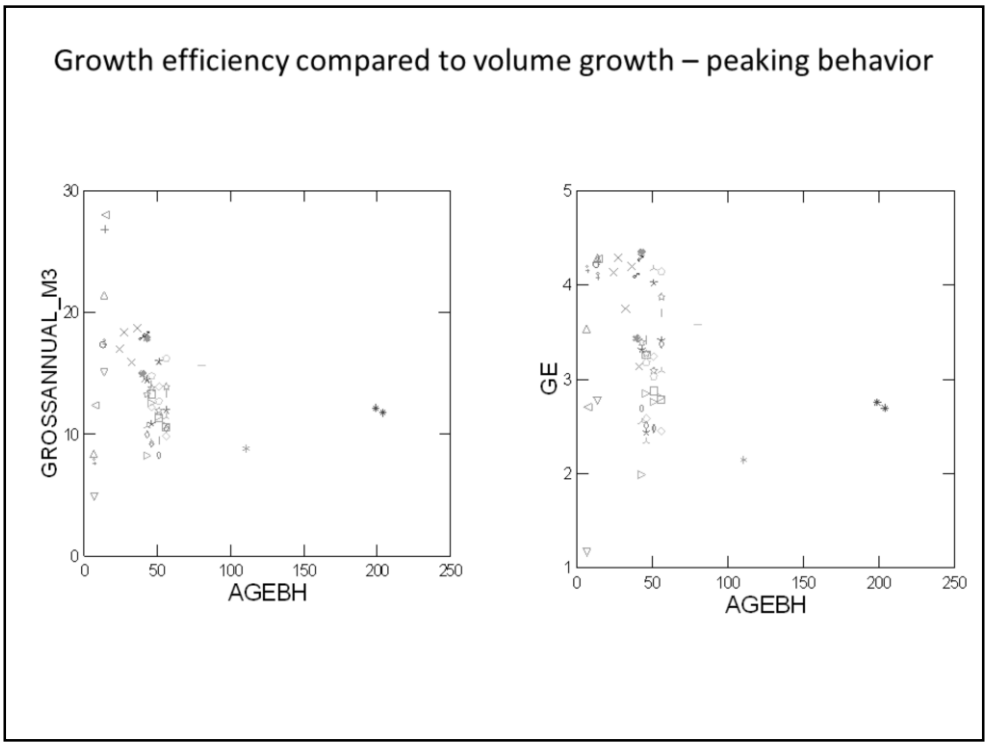


Parameter Estimates

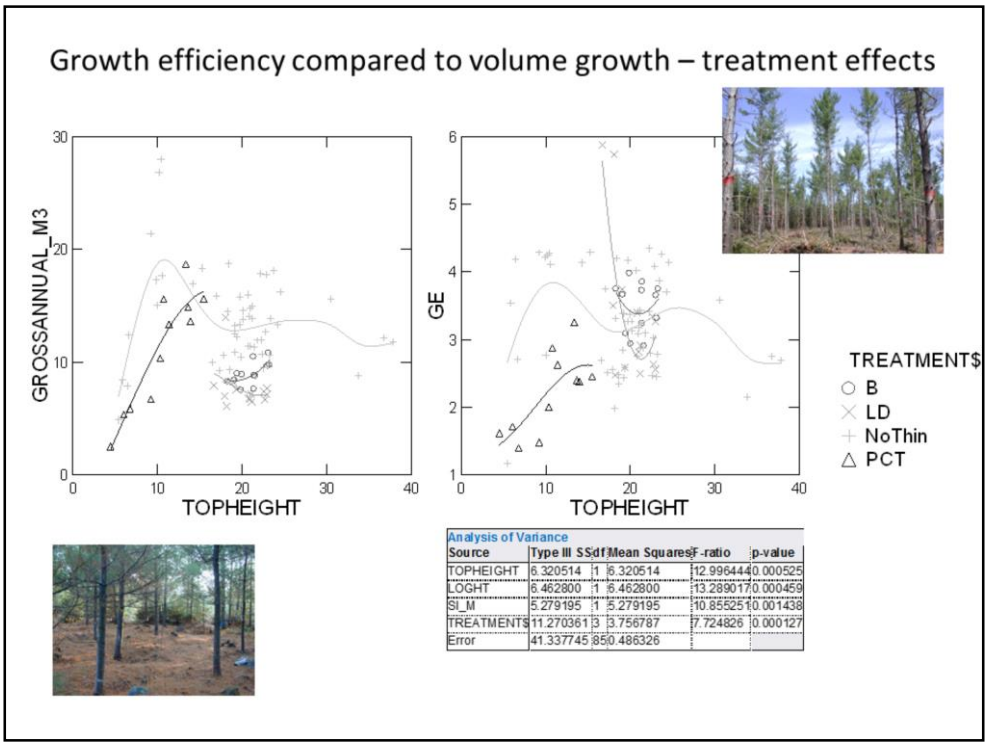
Parameter	Estimate	ASE	Parameter/ASE	Wald 95% Confidence Interval	
				Lower	Upper
A3	0.396594	0.035518	11.166097	0.325975	0.467212
A1	0.003453	.	.	.	.
A2	2.132533	0.355015	6.006881	1.426668	2.838399
B2	1,389.207834	260.759581	5.327543	870.747910	1,907.667758
B4	0.159761	0.012327	12.960695	0.135252	0.184270
C2	0.002215	0.002364	0.937181	-0.002485	0.006915
C3	18.637580	23.287751	0.800317	-27.664710	64.939871
C4	0.446554	0.179705	2.484921	0.089251	0.803856

GROSSANNUAL_M3 = (RELDENS^A3)*(A1*SI_M^A2)*(B2/(1+.001*EXP(B4*(AGEBH))) + 3000)*(C2/(1+C3*EXP(-C4*(AGEBH))))

Scatter plot of annual stemwood volume growth (gross) over age (Unthinned Plots Only). Double-logistic equation fitted to all data, including thinned plots. Parameters shown in table; $R^2 = 0.857$. Growth rates over 20 m^3 are unprecedented in the northeastern United States; the values achieved by two young plots (26 and 28 m^3, over 4 cords per acre per year, photo inset) are higher than any known published values for this region. Values for oven-dry biomass, carbon, and carbon dioxide equivalent can be calculated using the conversions given in the Methods.



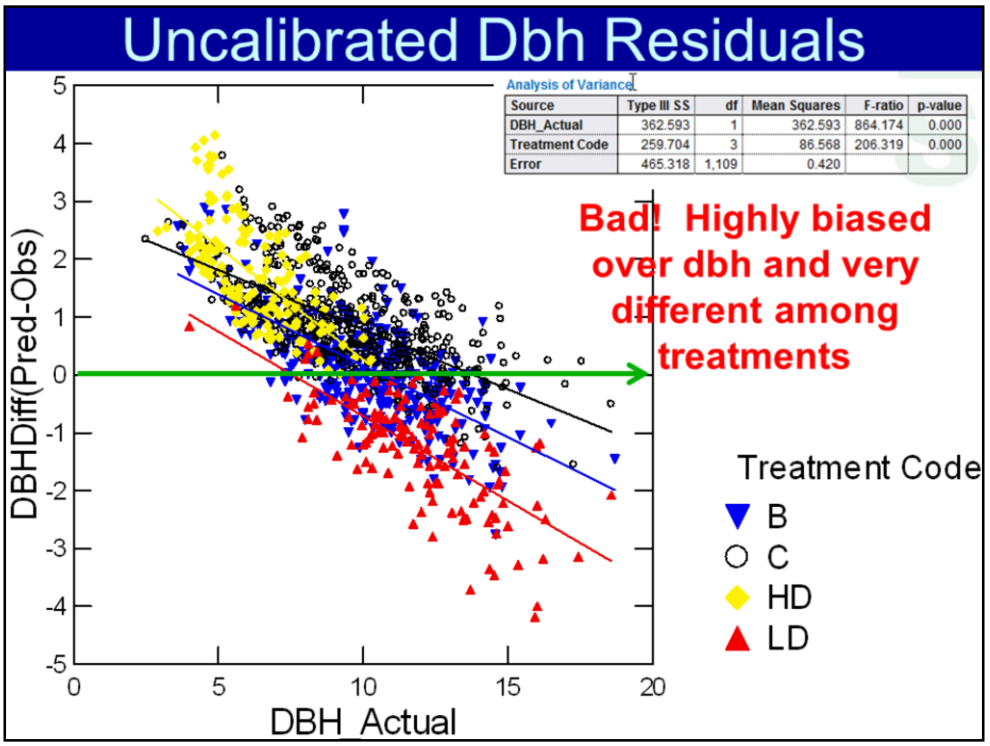
Scatter plot of stemwood growth efficiency (GE, m^3 stemwood per unit LAI) over age, compared to volume growth over age (unthinned plots only). Both metrics are highest in young (under 20) stands, but GE does not decline as rapidly. GE of the oldest plot (age 210) is as high or higher than at least 20% of those age 50 and younger.



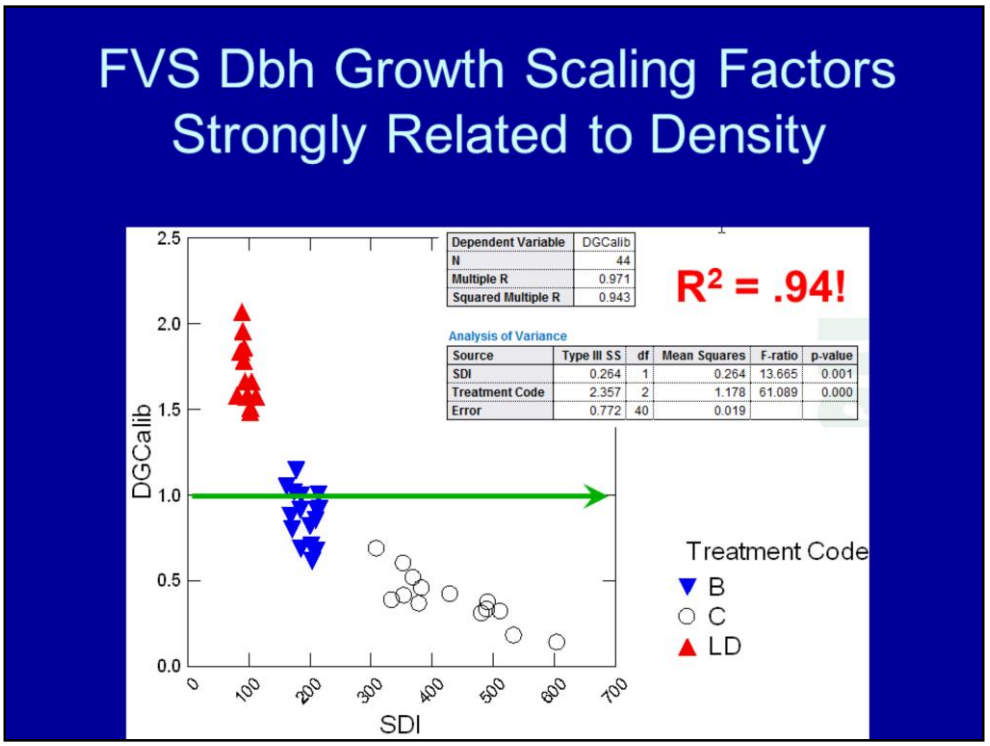
Analysis of Variance

Source	Type III SS	df	Mean Squares	F-ratio	p-value
TOPHEIGHT	6.320514	1	6.320514	12.996444	0.000525
LOGHT	6.462800	1	6.462800	13.289017	0.000459
SI_M	5.279195	1	5.279195	10.855251	0.001438
TREATMENTS	11.270361	3	3.756787	7.724826	0.000127
Error	41.337745	85	0.486326		

Scatter plot of stemwood growth efficiency (GE, m^3 stemwood per unit LAI) over age, compared to volume growth over stand top height, all treatments. Note that the high growth of two young plots is *not* due to higher GE, but simply very high LAI. (recall LAI patterns in earlier slides). Note also the low GE of the precommercially thinned plots; those are growing much less stemwood than unthinned plots of the same height and age, despite very similar LAIs. The highest GEs occurred on one plot thinned very heavily, to a low crop-tree density, at age 35, top height about 18 m. ANOVA on GE shows a peaking pattern with TopHeight (both TopHeight and Log of Topheight are significant), with highly significant effects of Site Index and Treatment. Mean separation reveals that the entire treatment effect is a result of the lower GE of the PCT plots relative to all others.



FVS validation: In the thinning study, diameter growth prediction was highly biased, both as a function of the tree's place in the dbh distribution, as well as the thinning treatment.



READCORD diameter growth calibration factors (Y-axis) were highly related to stand density index, a highly undesirable feature of any model, but a finding that suggests a way to improve the predictions.

Implications and applications in the Northern Forest region (1)

- This study suggests that eastern white pine is perhaps the most inherently productive species in the Northeast, at least in terms of stemwood volume growth, dry mass, and carbon.
- Dense young stands on high sites achieved volume growth rates that are unprecedented, approaching those of plantation southern pines, although most of this growth occurs in size classes that are not presently merchantable except as biomass.

Implications and applications in the Northern Forest region (2)

- Fully stocked old stands of white pine maintained rates of volume growth to age 200+, owing to stable leaf areas and relatively reasonable growth efficiency.
- Findings suggest that combining a long-rotation silvicultural system aimed at producing large pine sawlogs, with carbon offset payments to keep some of this carbon "on the stump" and growing, might be a win-win strategy for New England's white pine resource.
- A specific example: the 200-year-old stand in this study is sequestering nearly $ 3,000 worth of CO2 (at $12 a ton) above the common practice levels for the white pine forest type in this region.

Future directions

- The obvious next step for this work is to combine these data on white pine production ecology with studies of long-rotation silvicultural systems for high-value pine products, to ascertain whether there could be a hybrid system aimed at producing both sawlogs and carbon in combination.
- Another challenge is to find a way to capitalize on the very high productivity of dense young pine forests, which is currently impractical owing to small tree sizes and weak markets for biomass

List of products

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