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MANAGING FOR OLD-GROWTH STRUCTURE IN NORTHERN HARDWOOD FORESTS

William S. Keeton[1]

ABSTRACT

Recent research in the northeastern U.S. has focused on "structure" or "disturbance-based" silviculture. The as yet untested hypothesis is that these approaches can sustain a broader array of biodiversity and ecosystem functions than conventional systems. I am testing this hypothesis using a system that promotes old-growth structural characteristics, termed "Structural Complexity Enhancement (SCE)." This approach is compared against two conventional uneven-aged systems (single-tree selection and group-selection) modified to enhance post-harvest structural retention. The study is replicated at two mature, northern hardwood forests in Vermont. Manipulations and controls were applied to 2 ha units. The uneven-aged treatments were replicated twice; the SCE treatment and controls were each replicated four times. Structural objectives include multi-layered canopies, elevated large snag and downed log densities, variable horizontal density, and re-allocation of basal area to larger diameter classes. The latter objective is achieved using an unconventional marking guide based on a rotated sigmoid target diameter distribution, applied as a non-constant q-factor. The marking guide is also derived from a target basal area (34 m^2/ha.) and maximum diameter at breast height (90 cm) indicative of old-growth structure. Crown release was also used to promote growth in larger trees. Prescriptions for enhancing snag and downed woody debris density are based on stand potential. Forest structure data, including Leaf Area Index (LAI), detailed measurements of individual trees, and coarse woody debris (snags and downed logs) densities and volumes, have been collected over two years pretreatment and two years post-treatment. A before/after/control/impact approach was used to analyze these data. Fifty year simulations of stand development were run in NE-TWIGS, comparing alternate treatments and no treatment scenarios. Basal area retention, relative density, canopy closure, LAI retention, and coarse woody debris volumes and densities were significantly higher under the old-growth silvicultural system. Residual diameter distributions achieved the target rotated sigmoid form. There will be significant differences in stand development based on the simulation modeling. Late-successional structural and compositional characteristics will develop to a greater degree under SCE. Large tree (>50 cm dbh) recruitment will be impaired under the conventional treatments, whereas rates of large tree development will be significantly accelerated under SCE.

Keywords: Silviculture, old-growth, stand structure and development, northern-hardwoods.

INTRODUCTION

Recent research on sustainable forestry practices in the northern hardwood region of the United States and Canada[2] has focused on "structure" (Keeton et al. 2001) or "disturbance-based"

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[2] Includes all or portions of Minnesota, Wisconsin, Michigan, New York, Vermont, New Hampshire, and Maine in the United States, and Ontario, Quebec, New Brunswick, and Nova Scotia in Canada. Delineations sometimes also include portions of Pennsylvania and the southern New England states (Mladenoff and Pastor 1993).

(Seymour et al. 2002) silvicultural approaches. Structure-based forestry focuses on the architecture of forest stands in aggregate across the landscape or management units. Disturbance-based silviculture attempts to approximate the range of structural and compositional conditions associated with natural disturbance regimes. As complementary approaches, the shared operational objective is to explicitly manage for currently under-represented forest structures and age classes (Franklin et al. 2002) in densities and spatial configurations more similar to those associated with natural disturbance and successional dynamics (Seymour et al. 2002). In the northern forest region this includes managing for late-successional structure, which is vastly under-represented relative to the historic range of variability (Mladenoff and Pastor 1993, Cogbill 2000, Lorimer 2001).

Particular interest in structure-based silvicultural approaches has evolved from studies of old-growth northern hardwood and mixed hardwood-conifer forests. These have demonstrated the ecological significance of specific structural elements, such as large trees (live and dead), downed logs, multi-layered canopies, and horizontal variations in stand density and gap mosaics (Tyrell and Crow 1994b, Dahir and Lorimer 1996, McGee et al. 1999). Availability of these structures can be highly limited in forests managed under conventional even and uneven-aged systems (McGee et al. 1999). Managing for late-successional forests has the potential to enhance ecosystem services associated with structural complexity, such as a subset of wildlife habitats, carbon storage, and riparian functions. As a result, managing for old-growth structural characteristics, either in part or in full, is a proposed alternative silvicultural approach (Mladenoff and Pastor 1993; Keddy and Drummond 1996, Keeton et al. 2001).

While there has been much discussion of structure-based forestry in the theoretical literature, there have been few field trials or experimental tests in northern hardwood forests. An untested hypothesis is that silvicultural practices can accelerate rates of late-successional forest stand development (Franklin et al. 2002), promote desired structural characteristics, and enhance associated ecosystem functions more than conventional systems. I am testing this hypothesis using an approach, termed "Structural Complexity Enhancement (SCE), that promotes old-growth structural characteristics while also providing opportunities for timber harvest (Table 1). SCE is compared against two conventional uneven-aged systems (single-tree selection and group-selection) that are advocated regionally for sustainable forestry (Nyland 1998, Mladenoff and Pastor 1993). Uneven-aged silvicultural systems are sometimes viewed as more ecologically desirable than even-aged systems because they maintain continuous forest cover, although the latter have applications for early-successional habitat management. Conventional uneven-aged prescriptions employed in this study are modified to increase post-harvest structural retention and to represent best available practices. In addition, group-selection treatments are modified to approximate the average canopy opening size associated with fine-scale natural disturbance events in New England, based on the findings of Seymour et al. (2002).

The objectives for SCE are based on previous research describing old-growth northern hardwood and mixed northern hardwood-conifer forests (Gore and Patterson 1985, Woods and Cogbill 1994, Tyrrell and Crow 1994a and 1994b, Goodburn and Lorimer 1998, McGee et al. 1999, Ziegler 2000). They include multi-layered canopies, elevated large snag and downed log densities, variable horizontal density, and re-allocation of basal area to larger diameter classes. The latter objective is achieved, in part, using an unconventional marking guide based on a rotated sigmoid target diameter distribution. Rotated sigmoid diameter distributions have been widely discussed in the theoretical literature, but their silvicultural utility has not been field tested. Sigmoidal form is one of several possible distributions in eastern old-growth forests (Leak 1996 and 2002, Goodburn and Lorimer 1999). These vary with disturbance history, species composition, and competitive dynamics. The distribution offers advantages for late-successional structural management because it allocates more growing space and basal area (and thus biomass and structures associated with larger trees) to larger size classes. I predict that this distribution is sustainable in terms of recruitment, growth, and yield. If so, it would support O'Hara's (1998) assertion that there are naturally occurring alternatives to the negative exponential or "reverse-J" curve typically used in uneven-aged forestry. It would also suggest that silviculturalists have greater flexibility in managing stand structure, biodiversity, and other ecosystem functions in the northern forest region than previously recognized.

METHODS

Experimental Design

The study is conducted at the Mount Mansfield State Forest and at the University of Vermont's Jericho Research Forest. These are located on the western slopes of the northern Green Mountain in Vermont, U.S.A.. Study areas are mature, multi-aged, northern hardwood forests with minor shade-tolerant conifer components. There are three experimental manipulations. The first two are conventional uneven-aged systems (single-tree selection and group-selection) modified to enhance post-harvest structural retention. The modifications are based on a target residual basal area of 18.4 m^2/ha, max. diameter of 60 cm, and q-factor (the ratio of the number of trees in each successively larger size class) of 1.3. Group-selection cutting patches are each approximately 0.05 ha in size which results in 8 to 9 groups per treatment unit.

The third treatment is Structural Complexity Enhancement (SCE). The marking guide (the number of trees that must be cut in each size class to achieve the desired post-harvest structure) is based on a rotated sigmoid (see Leak 2002) target diameter distribution (number of trees per size class). This is applied as a non-constant q-factor: 2.0 in the smallest sizes classes, 1.1 for medium-sized trees, and 1.3 in the largest size classes. The marking guide is also derived from a target (desired future condition) basal area (34 m^2/ha.) and maximum diameter at breast height (90 cm) indicative of old-growth structure. Accelerated growth in larger trees is promoted through full (4 or 3-sided) and partial (2-sided) crown release. Prescriptions for enhancing coarse woody debris (CWD) volume and density are based on stand potential (e.g. pre-harvest CWD volume) and literature-derived targets. Snags were created by girdling diseased, dying, or poorly formed trees. Pre-treatment densities of low vigor trees were sufficient such that girdling of healthy trees was not necessary to achieve snag prescriptions. On one SCE unit at each of the two study areas, downed logs are created by pulling trees over, rather than felling, to create pits and exposed root wads.

Each of the first two treatments (uneven-aged) is replicated twice at Mount Mansfield; the third (SCE) is replicated four times, twice at each of the two study areas. Two un-manipulated control units are located at each study area. Treatment units are 2 ha in size and separated by 50 meter (min.) unlogged buffers to minimize cross contamination of treatment effects. Experimental manipulations (i.e. logging) were conducted on frozen ground in winter (Jan.-February) of 2003.

Data Collection

There are five, randomly placed, 0.1 ha permanent sampling plots in each treatment unit. Within each plot, all live and dead trees > 5 cm dbh and > 1.37 m tall were permanently tagged, measured, and recorded by species, diameter, height, and decay stage. Tree heights, height to crown base, and average crown width on each tagged tree were measured using an Impulse 200 laser range finder. Downed log (logs > 10 cm diameter) volume by decay class (1-5) was estimated using a line intercept method, while densities were measured across 0.1 ha plots. Leaf Area Index (LAI) was measured at five points in each plot using a Li-Cor 2000 meter. Two dominant canopy trees per plot were cored at breast height to allow subsequent laboratory determination of tree age and site index_{50}. Two years of pre-treatment and two years of post-treatment data collection have been completed.

Data Analysis

The Northeast Decision Model (NED) (Simpson et al. 1996) was used to generate stand inventory metrics based on pre and post-harvest sample data. NED data were exported to NED-SIPS ("Stand Inventory and Processing System") for stand development simulation using the NE-TWIGS model (northeastern U.S. variant of TWIGS), an individual tree-based, distance-dependent stand growth simulator (Hilt and Teck 1989). Fifty year projections of stand development were run for each treatment unit, including controls, using both pre and post-harvest scenarios. Cumulative basal area increment (CBAI) was calculated for each simulation run at 5 year intervals. Projections were normalized by calculating the differences in CBAI between "no-harvest" and "harvest" scenarios at each time step. The Kolmogorov-Smirnov two-sample goodness of fit test was used to test for differences between treatment groups along mean CBAI time series. Single-tree selection and group selection treatments were classified as one group ("conventional uneven-aged aged") for the purposes of these tests. This was appropriate because there were no significant differences among uneven-aged units in residual stand structure when data were aggregated to the unit scale. The log-likelihood ratio goodness of fit test (*G* test) was used to examine total CBAI developed after 50 years; response ratios (treatment vs. no treatment) were compared against a null ratio (no treatment effect). NE-TWIGS was also used to predict the number of large trees (two classes: > 50 cm and > 61 cm dbh) developed after 50 years. Sample data, including individual tree heights, crown dimensions, and CWD attributes, were also used as input for 3-dimensional modeling in the Stand Visualization System (SVS) (McGaughey 1997).

A Before/After/Control/Impact (Krebs 1999) statistical approach was used to compare pre-harvest and residual stand structure. Statistical analyses of structural variables included tests of means (e.g. ANOVA, Bonferroni multiple comparisons, *T*-tests) and tests of variance (e.g. *F*-tests). The latter were used to test equal variance assumptions. For three-way comparisons of residual structure at Mount Mansfield alone, plots were aggregated by treatment type rather than experimental unit. The "sampling frame" was defined as the continuous population of forest patches rather than arbitrarily imposed unit delineations (Stehman and Overton 1996). *F* tests of variance were used to evaluate consistency in post-harvest structure among units treated with the same prescription. To validate the use of plots as independent samples, spatial autocorrelation tests (Riply 1981) using the Moran coefficient (Moran 1950) were performed on relevant response variables using S-Plus statistical software (Kaluzny et al. 1998). Response data were sorted by treatment and made spatially explicit using geo-referenced plot positions. Spatial autocorrelation results were cross-checked against empirical variograms produced in S-Plus.

Diameter distributions (pre and post-harvest) are a useful indicator that integrates vertical and horizontal structural responses to treatment. To determine whether SCE successfully shifted diameter distributions towards the target rotated sigmoid form, pre- and post-harvest and target distributions were log transformed to enhance sigmoidal tendencies (Leak 2002). Residual distributions were smoothed using a Friedman smoothing run in S-Plus software. Kolmogorov-Smirnov two-sample goodness of fit tests were used to test for statistically significant differences between transformed residual and target cumulative frequency distributions. Residual distributions were created using real (sample) data for smaller diameter classes (<70 cm dbh) and hypothetical (e.g. future potential) values for larger diameter classes (>70 cm dbh). The latter borrowed values from the target distribution. Statistical tests, therefore, evaluated whether residual distributions achieved that portion of the target distribution possible given the pre-harvest structure.

RESULTS

Residual Stand Structure

Visualizations generated in SVS illustrate the high degree of structural complexity maintained by both SCE and single-tree selection (Figure 1). High levels of residual structure were maintained by all of the experimental treatments, including group selection. However, there were distinct differences. Canopy closure was highest for SCE (mean 77%) and lowest for single-tree selection units (mean 64%). These results were statistically significant ($P < 0.01$). Canopy closure, as expected, was most variable across group-selection units. Aggregate canopy closure remained high in group-selection units because 70- 80% of each group-selection unit was unlogged and thus maintained full pre-harvest structure. For investigations focused on Mount Mansfield, F tests of variance showed no significant differences ($\alpha = 0.05$) in post-harvest structure between similarly treated units. There was no significant ($\alpha = 0.05$) spatial autocorrelation among plots sorted by treatment; a result confirmed by empirical variograms. Individual plots were determined to be spatially independent samples based on these results.

There were significant differences ($P < 0.001$) in LAI responses among treatments. Single-tree and group selection cuts reduced LAI by 20 and 30% respectively. LAI reductions were lowest in SCE units (9%), indicating high retention of foliage bearing tree crowns and thus, by inference, vertical complexity. LAI was significantly more spatially variable for both SCE ($P = 0.031$) and group-selection ($P = 0.010$) compared to single tree selection; within-treatment variance was not significantly different between SCE and group-selection units ($P = 0.296$). These results are indicative of the high degree of horizontal structural variability expected for group-selection. In SCE units, increased horizontal complexity was achieved through variable density marking and clustered harvesting around crown-release trees.

A significantly higher level of residual basal area was maintained by SCE compared to either single tree selection ($P = 0.047$) or group selection ($P = 0.041$) units using aggregated, spatially independent plot data (n = 10 per treatment) for Mt. Mansfield only. Post-harvest relative density was also significantly greater in SCE units compared to single-tree selection ($P = 0.013$); it was not significantly greater than group-selection units ($P = 0.123$). There were no statistically significant differences ($\alpha = 0.05$) in variance within groups of plots aggregated by treatment. This result held for both pre and post-harvest structure.

SCE shifted residual diameter distributions to a form indistinguishable from the target rotated sigmoid form. There were no statistically significant differences ($\alpha = 0.05$) between residual and target distributions for any of the SCE units based on the goodness of fit test using log transformed diameter distributions (Figure 2). Future continued reallocations of basal area and stem density into larger size classes, yielding a rotated sigmoid distribution spanning a full range of diameter classes, are thus likely.

Crown Release and Vertical Development

Variable density harvesting resulted in crown release for 45 dominant trees per ha. on average in SCE units. When combined with the average pre-treatment number (20 per ha) of large trees (> 50 cm dbh), this exceeds our future target of 55 large trees per ha. The excess provides a "margin of safety" to accommodate canopy mortality. Crown release is likely to accelerate growth rates in the affected dominant trees by 50% or more based on previous modeling (e.g. Singer and Lorimer 1997). Dominant canopy trees were released across a range of diameter classes (>25 cm dbh); the majority were fully, rather than partially, crown released. Crown release also resulted in spatial aggregations of harvested trees, creating canopy openings and variable tree densities. Elevated light availability associated with clustered harvesting around crown release trees is likely to promote vertical differentiation of the canopy through release and regeneration effects. This will increase foliage density in the emergent and lower canopy layers over time.

Coarse Woody Debris Enhancement

SCE prescriptions resulted in substantially elevated densities of both downed logs and standing snags. The structural complexity enhancement treatments increased CWD densities by 10 boles (> 30 cm dbh) per ha on average for snags and 12 boles (> 30 cm dbh) per ha. on average for downed logs. Pulling trees over was successful in most cases at creating large exposed root wads and pits. There were statistically significant differences ($P = 0.002$) among treatments with respect to downed log recruitment effects (Figure 3). Post-harvest downed log volumes were 140% higher on average than pre-harvest levels in SCE units. Mean downed log volume increased 30% in the combined uneven-aged units, although this effect was not statistically significant relative to the controls. There were only slight (5% mean) increases in control units due to natural mortality; volumes declined in some control units. Background recruitment rates were thus not sufficient to explain SCE treatment effects. Analyses of downed log decay class distributions in SCE units showed, as expected, significant ($P < 0.05$) shifts towards less decayed logs due large inputs of felled trees.

Projected Stand Development

Stand development projections suggest that total basal area under SCE will, on average, approach 34 m^2/ha after 50 years of development. This is >50 % higher than the mean for the conventional uneven-aged units. However, this difference is attributable to the higher residual basal area left by SCE. The projections showed no significant differences in absolute growth rates between treatment scenarios, as measured by cumulative basal area increment (CBAI)

(Figure 4, top). When projected developed with treatment is normalized, to reflect the amount of development (specific to each unit) that would have been expected with no treatment, the simulations indicate that CBAI will be faster under conventional systems (Figure 4, bottom). Both SCE ($P < 0.05$) and conventional treatments ($P < 0.01$) are projected to significantly accelerate tree growth rates above that expected with no treatment based on NE-TWIGS modeling. Total projected CBAI after 50 years was 12.5 m^2/ha (no treatment) compared to 28.0 m^2/ha (with treatment), on average, in SCE units. For conventional units, total mean projected CBAI increased from 1.5 m^2/ha (no treatment) to 23 m^2/ha (with treatment).

SCE is projected to significantly enhance rates of large tree recruitment over no treatment scenarios. There will be an average of 17 more large trees (> 50 cm dbh) per ha than there would have been without treatment after 50 years in SCE units. There will be 29 fewer large trees per ha on average in the conventional units than would have developed in the absence of timber harvesting (Figure 5).

DISCUSSION

Silvicultural techniques can be used effectively to promote old-growth structural characteristics in northern hardwood and mixed northern hardwood-conifer forests. Both the uneven-aged approaches tested and SCE maintain high levels of post-harvest structure and canopy cover. However, SCE maintains, enhances, or accelerates develop of CWD, canopy layering, overstory biomass, large tree recruitment, and other structural attributes to a greater degree. The higher levels of structural retention associated with SCE are indicative of lower intensity, minimal impact forestry practices.

Both SCE and conventional uneven-aged treatments will result in accelerated tree growth rates according to simulation projections. Since the conventional treatments retained less basal area, their comparatively higher projected basal area increment is consistent with previous research on growth responses to stocking density (Leak et al. 1987). It is important to note, however, that the NE-TWIGS model is not spatially explicit. Inter-stem competition and tree growth rates are simulated as a function only of total stand stocking (within size classes) and not the spatial position of individual trees. The model does not, therefore, capture the effects of crown release employed in SCE. Since crown release is likely to significantly increase growth rates in selected dominant trees (Singer and Lorimer 1997), spatially explicit simulation modeling may result in different, and possibly enhanced, developmental projections for SCE. Regardless, an important effect of SCE is the promotion of large tree recruitment, whereas this process is impaired under conventional treatments that include maximum diameter limits. Projected basal area is also higher after 50 years of development under SCE due to elevated post-harvest structural retention.

SCE resulted in significantly elevated CWD densities and volumes. However, it remains uncertain whether this effect will persist until natural recruitment rates increase, or, alternatively, whether CWD enhancement in mature stands has only transient or short-term management applications. While long-term CWD persistence and accumulation dynamics are uncertain, it is likely than decay class distributions will again shift over time towards better decayed material. This would render silviculturally enhanced CWD more biologically available in habitat and nutrient processes in the future (Gore and Patterson 1985, Tyrrell and Crow 1994, Goodburn and Lorimer 1998).

SCE may have a variety of useful applications, depending on economic feasibility, ranging from old-growth restoration, to riparian management, to low-intensity timber management and late-successional wildlife habitat enhancement. Depending on the specific application, SCE could be employed to varying degrees or to a more limited extent. For instance, where timber production is emphasized, a subset of SCE elements might be used. Other elements might be avoided or employed at a lesser intensity. In this scenario, multiple stand entries would be expected, but late-successional structural development would be lower compared to full SCE implementation. Such an approach, however, would allow forest managers to build some degree of old-growth associated structure into actively managed stands, while maintaining greater timber management flexibility. Managers of protected areas, conversely, might choose to employ SCE more fully. They might enter a stand once or twice, thereafter allowing accelerated successional processes to take over. The degree of implementation and the number of stand entries will thus vary by application.

Forest managers have the flexibility to manage for a wide range of structural characteristics and associated ecosystem functions. Uneven-aged systems provide some, but not all, late-successional structural characteristics or provide them to a more limited extent. Residual basal area, maximum diameter, and *q*-factor can be modified singly or collectively, resulting in greater structural retention. However, maximum diameter limits significantly retard the potential for large tree (live and dead) recruitment based on the results. Stand development is thus continuously truncated by multiple uneven-aged cutting rotations or entries. The results show that SCE's variable *q*-factor marking guide can be used to successfully achieve a rotated sigmoid diameter distribution. Unconventional prescriptive diameter distributions, such as the rotated sigmoid, combined with higher levels of residual basal area, very large (or no) maximum diameters, and crown release are another alternative for retaining high levels of post-harvest structure and for promoting accelerated stand development.

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Table 1. Structural objectives and the corresponding silvicultural techniques used to promote those attributes in Structural Complexity Enhancement

Structural Objective	Silvicultural Technique
Multi-layered canopy	• Single tree selection using a target diameter distribution • Release advanced regeneration • Establish new cohort
Elevated large snag densities	• Girdling of selected medium to large sized, low vigor trees
Elevated downed woody debris densities and volume	• Felling and leaving, or • Pulling over and leaving
Variable horizontal density	• Harvest trees clustered around "release trees" • Variable density marking
Re-allocation of basal area to larger diameter classes	• Rotated sigmoid diameter distribution • High target basal area • Maximum target tree size set at 90 cm dbh
Accelerated growth in largest trees	• Full and partial crown release of largest, healthiest trees

List of Figures

Figure 1. Output of the Stand Visualization System (SVS) contrasting single-tree selection Unit 4 (above) and Structural Complexity Enhancement (SCE) Unit 2 (below) at the Mount Mansfield study area. Shown are images of pre- and post-harvest stand structure for 1 ha. blocks. Shaded circles represent tree crowns (with species-specific coloration) seen from a simulated aerial view. Note the high degree of post-harvest structure (e.g. basal area and stem density), canopy closure, vertical complexity, and downed log densities in the SCE unit. Note the similar, though lower, degree of structural retention in the single-tree selection unit.

Figure 2. Pre-harvest, post-harvest, and target diameter distributions for the four SCE units, two at Mt. Mansfield (above) and two at the University of Vermont's Jericho Research Forest (below). Log transformed post-harvest and target distributions are compared (top portion of graphs) using the Kolmogorov-Smirnov two-sample goodness of fit test. There were no statistically significant differences. Thus, the post-harvest distributions achieved the target rotated sigmoid distribution.

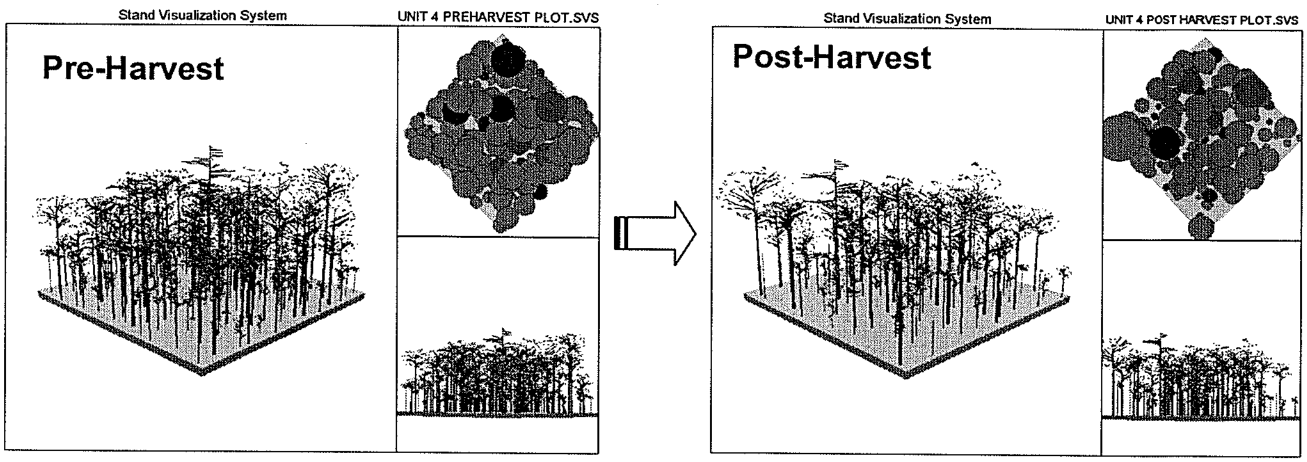
Figure 3. Downed log response to treatments. Shown are percent change from pre-harvest levels and absolute change in volume (m^3/ha). Error bars are ±1 standard error of the mean.

Figure 4. Results of NE-TWIGS stand development modeling. Shown are cumulative basal area increment (CBAI, live tree) for 50 year projections of post-harvest structure (top) and normalized scenarios (post-harvest minus pre-harvest CBAI). Error bars are ±1 standard error of the mean

Figure 5. Projected change in large tree densities after 50 years. Values represent the difference between treatment and no treatment scenarios. Note the increased recruitment of large trees under SCE versus the impairment of large tree recruitment under the conventional uneven-aged treatments.

Figure 1

Single-Tree Selection Unit



Structural Complexity Enhancement Unit

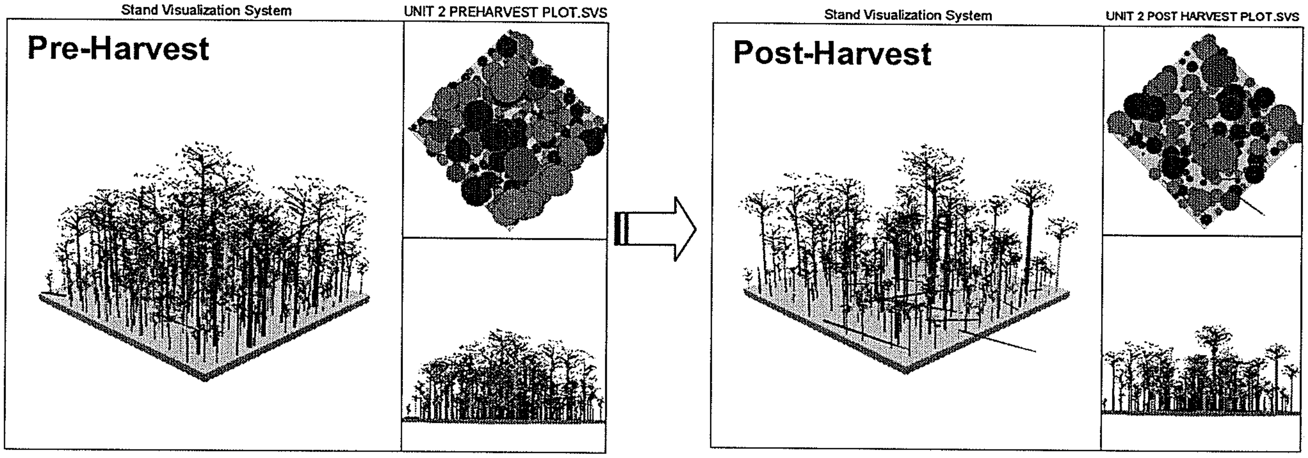


Figure 2

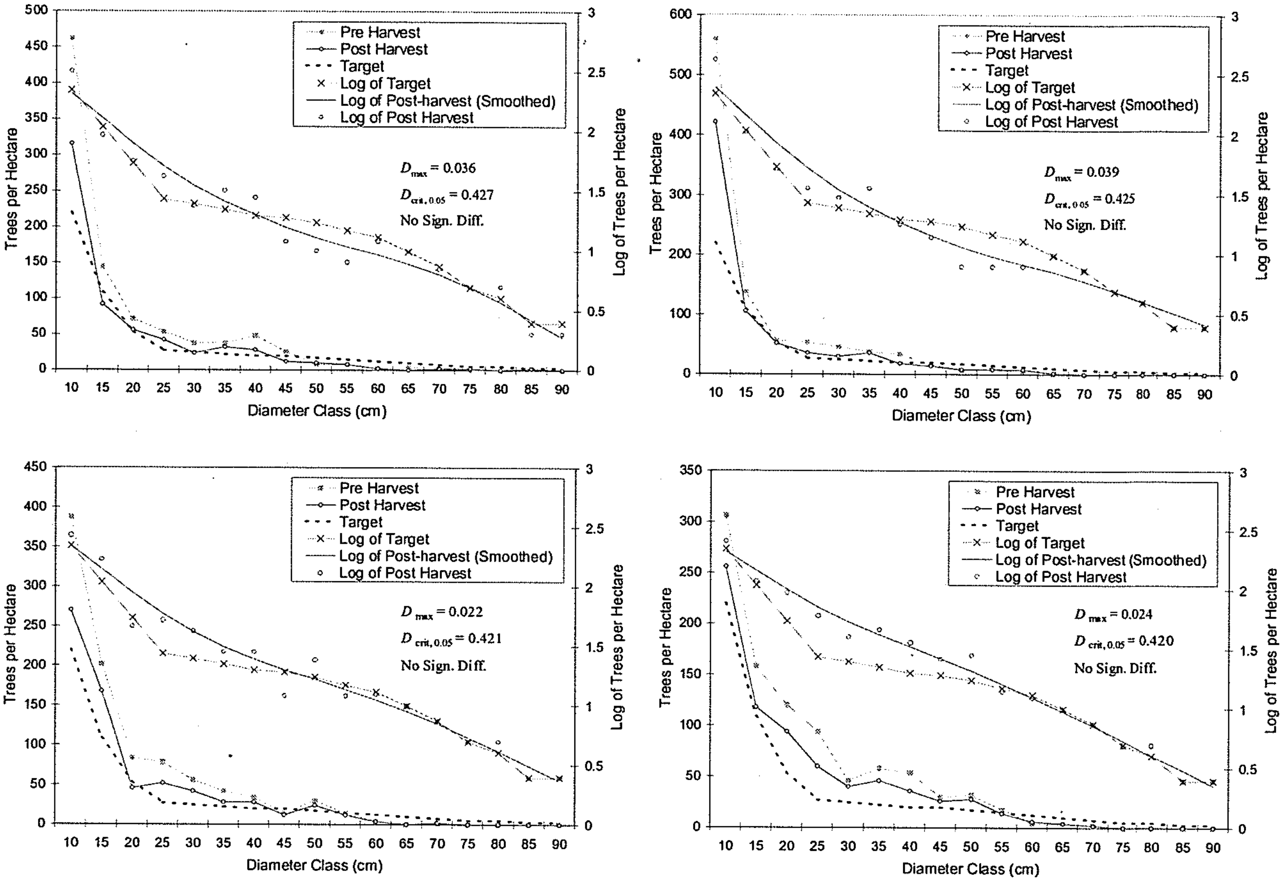


Figure 3

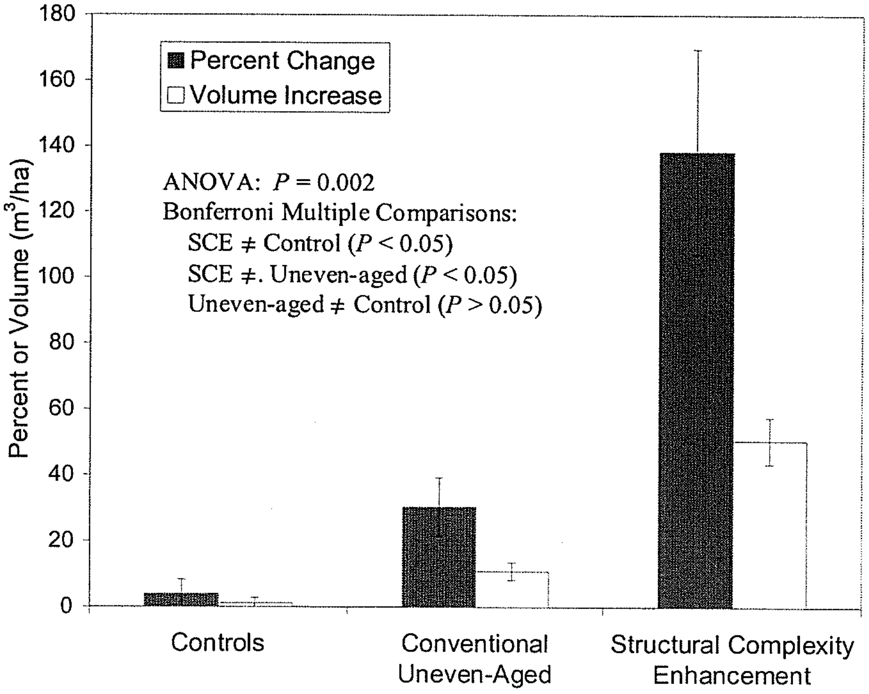
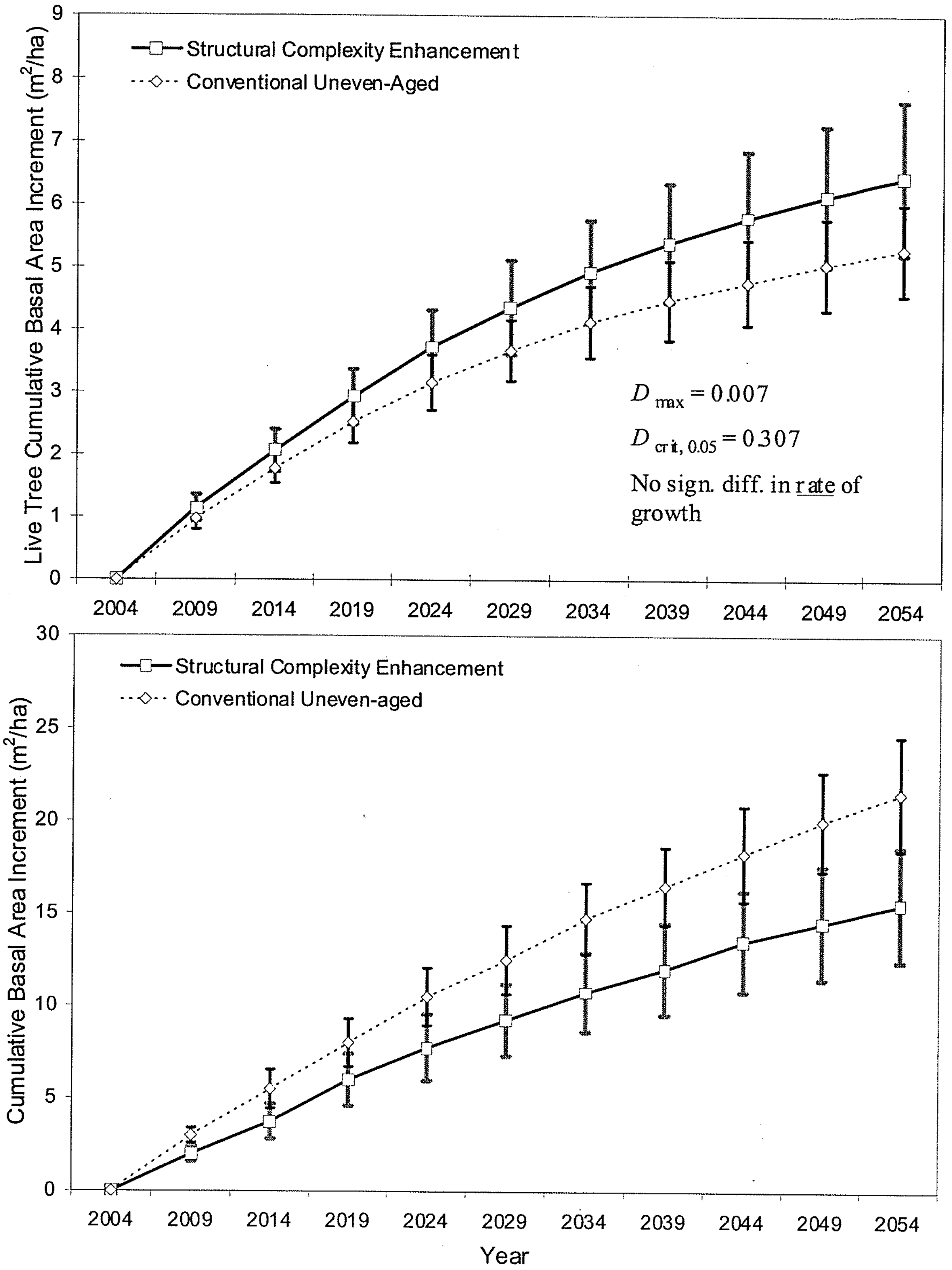
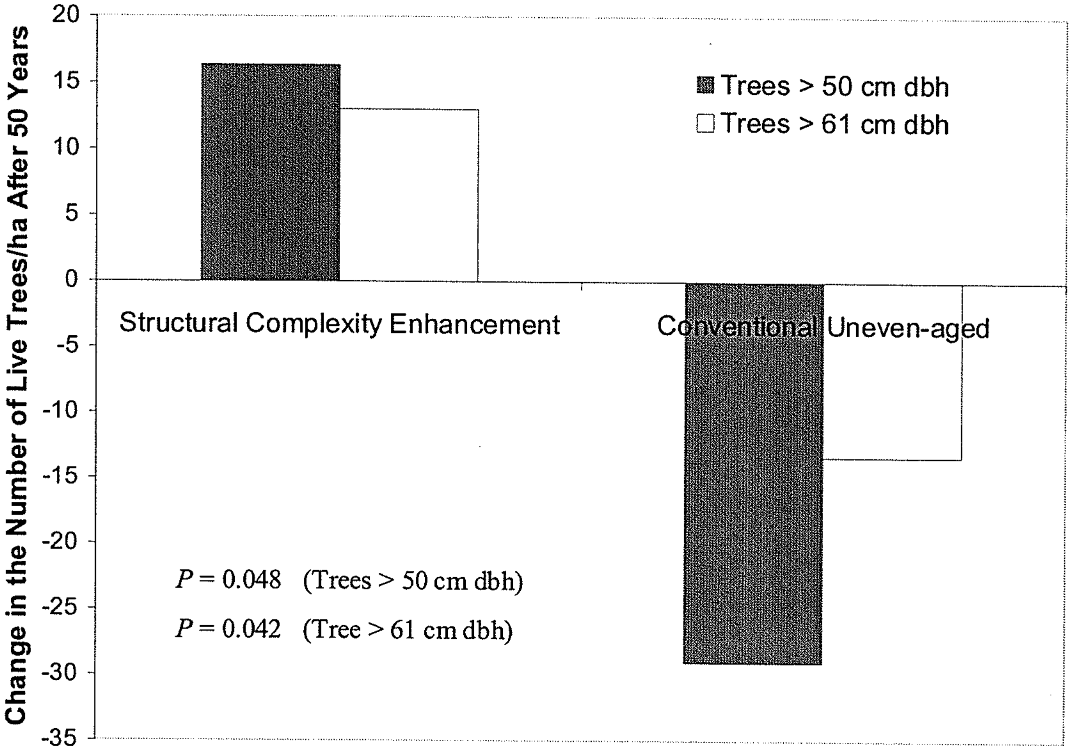


Figure 4



Structural Complexity Enhancement
Conventional Uneven-Aged
Live Tree Cumulative Basal Area Increment (m^2/ha)
0
1
2
3
4
5
6
7
8
9
$D_{\max} = 0.007$
$D_{\mathrm{crit},\,0.05} = 0.307$
No sign. diff. in rate of growth
2004
2009
2014
2019
2024
2029
2034
2039
2044
2049
2054
Structural Complexity Enhancement
Conventional Uneven-aged
Cumulative Basal Area Increment (m^2/ha)
0
5
10
15
20
25
30
2004
2009
2014
2019
2024
2029
2034
2039
2044
2049
2054
Year

Figure 5


Change in the Number of Live Trees/ha After 50 Years
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
▨ Trees > 50 cm dbh
☐ Trees > 61 cm dbh
Structural Complexity Enhancement
Conventional Uneven-aged
P = 0.048 (Trees > 50 cm dbh)
P = 0.042 (Tree > 61 cm dbh)