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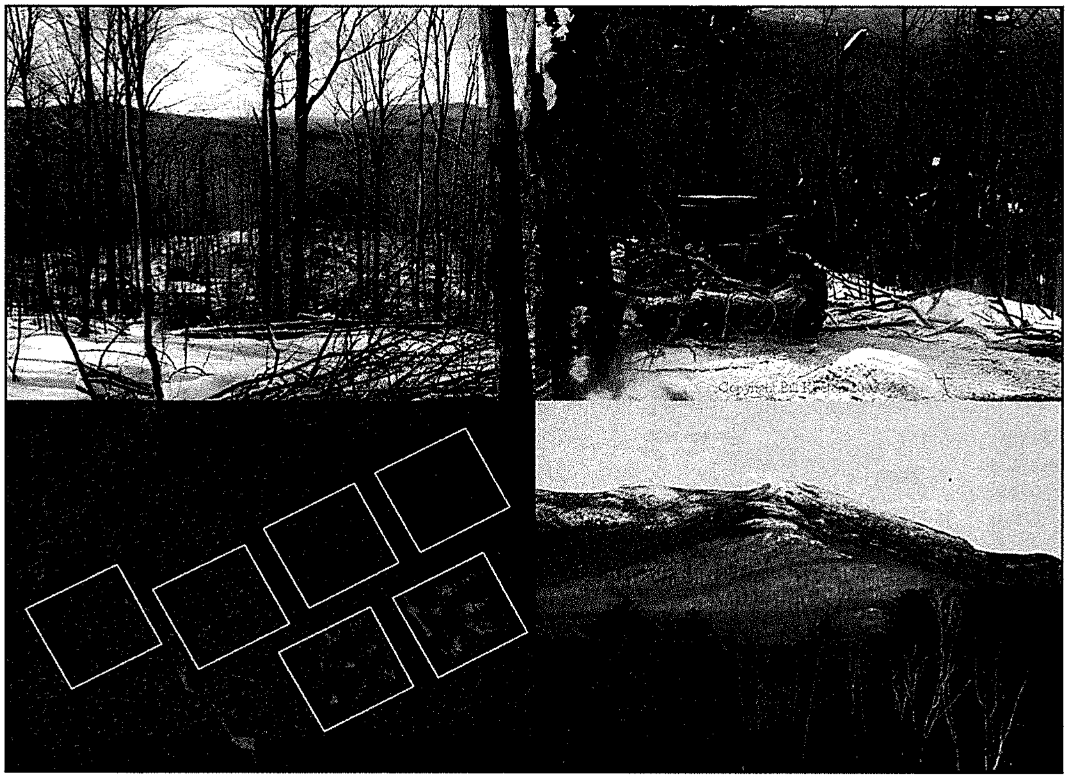
The Vermont Forest Ecosystem Management Demonstration Project

2004 Research Report



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EXECUTIVE SUMMARY

This report summarizes the first three years of the Vermont Forest Ecosystem Management Demonstration Project (FEMDP), including design, implementation, and preliminary data analysis. The FEMDP is an interdisciplinary research program evaluating the ecological and economic effects of sustainable forest management techniques for the northern forest region. The FEMDP is testing the hypothesis that "structure-based" and "disturbance-based" forestry practices – approaches advocated regionally but largely untested experimentally – can sustain a broader array of biodiversity and ecological functions while also providing opportunities for profitable timber management. Systems tested include uneven-aged prescriptions (single-tree selection and group-selection) modified to enhance structural retention and emulate the scale and pattern of low-intensity natural disturbance effects. They also include a new silvicultural approach that we term "structural complexity enhancement" (SCE). This approach promotes old-growth forest characteristics and associated ecological functions by accelerating stand development processes.

The FEMDP is being conducted on the Mount Mansfield State Forest and at UVM's Jericho Research Forest. At Mount Mansfield the experimental design consists of eight treatment units (six manipulations and two controls) each of which is 2 ha. in size; only the structural complexity enhancement units and controls are replicated at Jericho. Manipulations (i.e. logging) were conducted in winter and early spring of 2003. Two years of pre-treatment and one year of post-treatment data collection have been completed. Key ecological response variables include residual stand structure; tree regeneration, growth, and mortality rates; understory plant communities; forest health; above-ground carbon sequestration; soil invertebrates and macro-nutrients; small mammals; amphibians; and avian habitat quality. Economic research will evaluate tradeoffs among the systems tested and is determining the site and market conditions necessary for structure-based systems to be economically viable and profitable.

INTRODUCTION

The Northern Forest Lands Council, in its report "Finding Common Ground," recognized that new ways of managing forests, including innovative silvicultural systems, are needed if the region's forests are to provide "a wide range of benefits," including non-timber values. The Council recommended that forest managers find ways of balancing multiple objectives, including "maintenance or creation of a healthy balance of forest age classes" and "conservation and enhancement of habitats that support a full range of native flora and fauna." The Vermont Forest Ecosystem Management Demonstration Project (FEMDP) is a response to the Council's recommendations: it is evaluating the potential of alternate silvicultural systems to balance ecological and economic objectives.

The FEMDP has the goal of bringing together researchers from diverse fields in an experimental test of forest management effects on northern hardwood ecosystems. The FEMDP is specifically designed to provide a framework for multiple or supplemental research components to be added as interest and expertise allow. Coordinated by the Vermont Monitoring Cooperative (VMC), FEMDP is providing policy makers and forest managers with ecological and socio-economic information on a range of sustainable forest management options. The FEMDP is also helping forest managers evaluate the benefits, tradeoffs, and feasibility of structure-based, uneven-aged and restorative silvicultural systems. The project is generating information that is particularly relevant to forest managers involved in sustainable forest management planning, transfers of development rights, and "green" certification (Keeton et al. 2001). Stakeholder response to the FEMDP has been unequivocally positive in terms of applications to a wide range of forest management scenarios.

PROJECT OBJECTIVES

The FEMDP has five primary objectives. These are:

1. encourage inter-disciplinary research collaboration on sustainable forestry practices;
2. evaluate the ability of alternative silvicultural systems to promote late-successional forest characteristics and associated ecological functions;
3. evaluate the ecological effects, including impacts on biodiversity at the stand level, of structure- and disturbance-based forestry practices;
4. determine the economic potential for, and tradeoffs among, alternate sustainable forestry systems; and
5. transfer information on silvicultural options to stakeholders and forest managers.

BACKGROUND AND JUSTIFICATION

Recent research on sustainable forestry practices in the northern hardwood region of the United States and Canada has focused on "structure" (Keeton et al. 2001) or "disturbance-based" (Mitchell et al. 2002, Seymour et al. 2002) silvicultural approaches. Structure-based forestry focuses on the architecture of forest stands in aggregate across the landscape or management units, with a broad goal of providing the full array of structural conditions associated with stand development, including early, mid, and late stages of development. The operational objective is to explicitly manage for currently under-represented forest structures and age classes (Franklin et al. 2002) in densities and spatial distributions more similar to those associated with natural disturbance and successional dynamics (Aplet and Keeton 1999, Seymour et al. 2002). In the northern forest region this typically means managing for late-successional structure, which is vastly under-represented relative to the historic range of variability (Foster 1992, Mladenoff and Pastor 1993, Foster et al. 1998, Cogbill 2000). The possibility of managing for early-successional habitats is also topic of considerable debate in this region, but is not addressed by the FEMDP.

Managing for a diversity of forest structures provides a coarse-filter conservation approach for the biodiversity associated with those structures (Aplet and Keeton 1999). Like many active forest management approaches, however, this carries risks and uncertainties, particularly for sensitive species. Thus, structure-based forestry represents a conservation tool to be used in conjunction with other approaches, such as protected areas. If structure-based silvicultural systems prove effective, they will provide greater flexible in managing forest stands. Yet they would need to be employed within the larger ecosystem management context (consisting of multiple forest management approaches) in order to achieve sustainability objectives.

In theory, managing for late-successional forest structure offers an alternative to more intensive forest management practices. It has the potential to enhance ecosystem services associated with structurally complex, late-successional forest stands, such as a subset of wildlife habitats, carbon storage, and riparian functions. Whether or not this approach might also generate sufficient timber revenue to be commercially viable has not been previously tested. 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 (McGee et al. 1999, Tyrell and Crow 1994b). Availability of these structures can be highly limited in forests managed under conventional even and uneven-aged systems where these truncate or retard stand development potential (McGee et al. 1999). As a result, managing for old-growth structural characteristics, either in part or in full, is a proposed alternative silvicultural approach in the northern forest region (Mladenoff and Pastor 1993; Trombulak 1996; 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 of underlying assumptions. An important, yet largely untested, hypothesis is that these systems can sustain a broader array of biodiversity and ecosystem functions than conventional systems. The FEMDP is testing this hypothesis using an approach that promotes old-growth structural characteristics. This approach, termed "Structural Complexity Enhancement," is compared against two conventional uneven-aged systems (single-tree selection and group-selection) modified to enhance post-harvest structural retention. There are several areas of particular interest, including differences between natural disturbance and forest management effects, impacts on both native and exotic biodiversity, forest health dynamics, and impacts on ecosystem processes, such as nutrient cycling, carbon storage, and hydrologic regimes. Economic tradeoffs and market considerations relative to the feasibility of structure-based systems also are of key interest to collaborating researchers.

Table 1. Structural characteristics of old-growth hemlock-northern hardwood forests.*

Structural Attribute	Minimum Requirement	Average Value in PA	Avg. Value in NY
Very Large Hemlocks	>3/ha > 70 cm dbh	19/ha	
Large Hemlocks	> 30/ha > 50 cm dbh	45/ha	
Large Trees of All Species	> 40/ha > 50 cm dbh	94/ha	55/ha
Coarse Woody Debris (Hemlock Only)	> 50 m^3/ha	171 m^3/ha	
Coarse Woody Debris (All Species)	> 100 m^3/ha	275 m^3/ha	
Downed Logs (Hemlock Only)	> 25 m^3/ha	142 m^3/ha	
Downed Logs (All Species)	> 55 m^3/ha	204 m^3/ha	139 m^3/ha
Downed Logs in Advance Decay	> 20 m^3/ha	93 m^3/ha	
Hemlock Snag Basal Area	> 0.5 m^2/ha	2.7 m^2/ha	
Hemlock Snag Volume	> 15 m^3/ha	32.9 m^3/ha	
Snag Basal Area (all Species)			8.6 m^2/ha
Snag Density (All Species >10 cm dbh)			42.8/ha
Canopy Gap Area	> 3.5 % of stand	5.8	
Canopy Gap Size	> 30 m^2 mean canopy gap size	143	

* Data from Tyrrell and Crow (1994a; 1994b); Haney and Schaadt (1996); and McGee et al. (1999)

Table 2. Indicators of old-growth character in eastern deciduous forests.*

Indicator	Measurement	Suggested Value
Tree Size	Basal area (m2) per hectare	> 29
Canopy Composition	Proportion of shade-tolerant tree species	> 70%
Coarse Woody Debris	Megagrams per hectare	> 20
	Presence of large decaying logs (> 8 logs/ha)	
Herbaceous Layer	Number of ephemeral species	≥ 6
Corticulous Bryophytes	Number of bryophyte species	≥ 7
Large Diameter Snags	Number of snags (> 50.8 cm dbh) per 10 hectare	≥ 4
Mycorrhizal Fungi	No information	

* Adapted from Keddy and Drummond (1996)

The objectives for Structural Complexity Enhancement (SCE) are based on previous research (Tables 1 and 2) describing old-growth northern hardwood forests (e.g. McGee et al. 1999; Goodburn and Lorimer 1998; Tyrrell and Crow 1994a, 1994b; Gore and Patterson 1985). They include multi-layered canopies, elevated large snag and downed coarse woody debris (CWD) densities, variable horizontal density, and re-allocation of basal area to larger diameter classes. The later 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 2002, 1996; Goodburn and Lorimer 1999). These vary with disturbance history 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. Silviculturalists may have greater flexibility in managing stand structure, biodiversity, and other ecosystem functions in the northern forest region than previously recognized. Management for old-growth characteristics, specifically, may enhance certain ecological functions, such as carbon sequestration, and habitat quality for a subset of species that are currently under-represented regionally.

Rationale for Experimental Treatments

FEMDP researchers are investigating a spectrum of silvicultural treatments variably termed disturbance-based (Mitchell et al. 2002, Seymour et al. 2002), structure-based (Franklin et al. 1997), or multi-aged forestry (O'Hara 1998). To this end the project includes two disparate sets of treatments. The first set represent uneven-aged approaches advocated regionally for sustainable forestry (Nyland 1998, Mladenoff and Pastor 1993). The FEMDP modifies these slightly (by adjusting BD*q* prescriptions) to increase post-harvest structural retention and address specific forest health concerns, particularly beech bark disease. As such, the uneven-aged treatments represent "best available practices" rather than an alternative to current practices. Uneven-aged silvicultural systems are sometimes viewed as more ecologically desirable than even-aged systems because they maintain continuous forest cover. However, their effects on flora and fauna, as well as certain ecological processes, are not completely understood; they typically result in shifts in community composition over time and truncated structural development. Moreover, researchers have recently recommended smaller group selection units (or patches) then the ¼ to ½ acre patch sizes typically employed in the northern forest region. Seymour et al. (2002) found that canopy damage caused by non-catastrophic disturbances in New England historically were 1/8 acre in average extent; they suggested that groups intended to mimic the scale of natural disturbance effects should be designed accordingly. This recommendation has not yet been tested and tree regeneration effects are uncertain. Evaluating the positive and negative potential of these systems – from silvicultural, economic, and ecological perspectives – is an important component of the FEMDP.

Table 3. Structural objectives and the corresponding silvicultural techniques used to promote those attributes in the Structural Complexity Enhancement approach

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

The second set of treatments address a growing regional interest in managing for a diversity of forest structural conditions, including those associated with natural disturbance effects (Seymour et al. 2002) and late-successional forest development (Mladenoff and Pastor 1993). The treatments are designed to promote structural complexity (Table 3) and the associated biodiversity and ecosystem functions by accelerating rates of stand development (Aplet and Keeton 1999, Franklin et al. 2002). Termed "structural complexity enhancement"(Keeton et al. 2001), this experimental system builds on previous research that identified structural characteristics associated with mature and old-growth northern hardwood and mixed hardwood/conifer forests and tested the effects of treatments on a subset of these.

Biodiversity Indicators

The FEMDP is focusing on a number of taxa selected as useful and meaningful indicators of biodiversity responses to silvicultural treatment. Taxa were selected based on four criteria: 1) ecological significance; 2) habitat requirements related to aspects of forest structure and within-stand environmental conditions likely to be modified by the experiment; 3) population or habitat quality responsiveness at scales detectable by our sampling methodology; and 4) potential use as environmental and forest management indicators based on published scientific literature. Biodiversity indicators monitoring by the FEMDP include vegetation (overstory and understory; vascular and non-vascular), birds, small mammals, amphibians, and soil invertebrates (Carabid beetles and Collembola). The author is responsible for vegetational (w/ Laurel William, UVM graduate student) and amphibian (w/ Heather McKenny, UVM graduate student) research, whereas collaborating researchers (D. Tobi, M. Skinner, C.W. Kilpatrick, and A. Strong) are the primary investigators for other taxa. This progress report addresses only vegetational responses to FEMP treatments.

Economic Tradeoffs

A central goal of the FEMDP is to evaluate the economic feasibility of different approaches for managing northern hardwood ecosystems. The economics of these systems, particularly those that promote structural complexity, are poorly understood. Previous research has shown that revenue and product type vary widely with even small modifications to uneven-aged prescriptions (Niess and Strong 1992, Buongiorno et al. 1994, Niese et al. 1995). Moreover, little information exists on the potential economic returns to alternative silviculture practices in northern hardwood forests. For alternative silvicultural approaches to have appeal for private woodlot owners and forest managers, their operational and economic feasibility must be demonstrated. For this reason, the FEMDP is evaluating economic feasibility from a present value framework, factoring in the price uncertainty stemming from the output of diverse products. This analysis will allow us to address the following questions: What are the economic tradeoffs involved with varying intensities of timber removal versus habitat enhancement? What is the economic viability of the alternative silvicultural models under different scales of production? What is the level of economic uncertainty of these systems? What factors beyond stumpage volume, price and interest rates affect economic feasibility and risk? Economic research is conducted by A. Troy and C. Danks in collaboration with other FEMDP researchers. Consequently, it will not be addressed further by this research report.

METHODS

Study Areas and Experimental Design

The FEMPD is conducted at the Mount Mansfield State Forest and at the University of Vermont's Jericho Research Forest (Figures 1 and 2). Study areas are mature, multi-aged, northern hardwood forests with minor shade-tolerant conifer components. Tree coring across size classes confirmed that the research sites were multi-aged due to previous management history, thereby negating potential high-grading concerns. We are testing three silvicultural systems. These are applied to 2 ha experimental treatment units. Each of the first two treatments (uneven-aged) are replicated twice (additional replicates are provided by the USDA Forest Service, Northeastern Research Station); the third is replicated four times. Two un-manipulated control units are located at each study area. Treatment units are separated by 50 meter (minimum) buffers (limited entry only along skid trails) to reduce possible cross contamination of treatment effects. Visual buffers (no entry zones) are maintained along recreational trails (Figure 1).

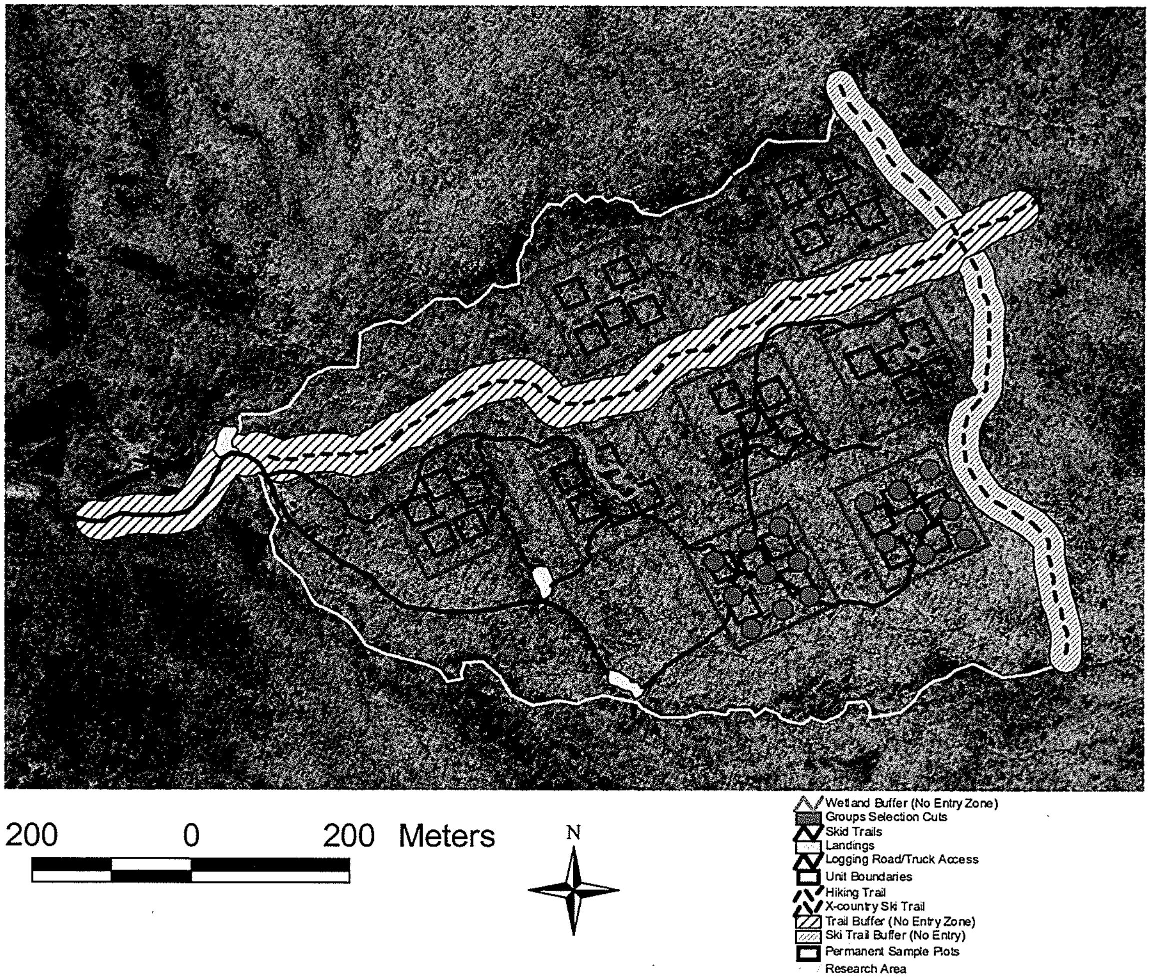


Figure 1. Experimental design and layout of the 2 ha. treatment units and 0.1 ha. permanent sampling plots at the Mt. Mansfield State Forest.

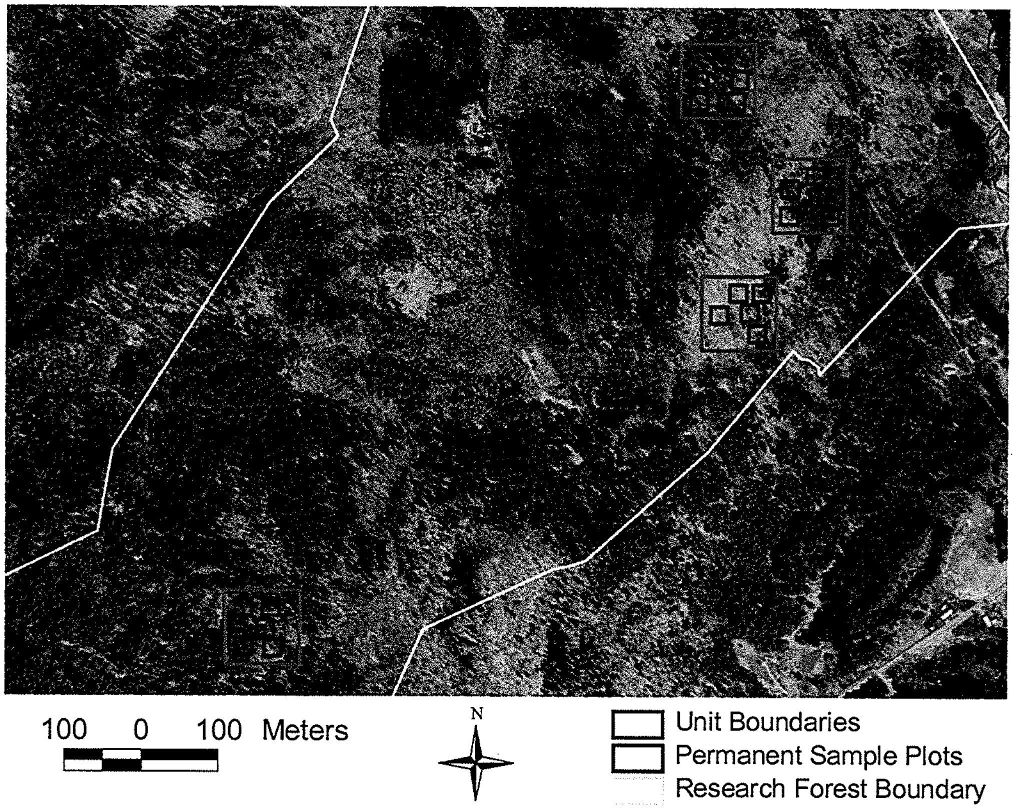


Figure 2. Experimental design and layout of the 2 ha. treatment units and 0.1 ha. permanent sampling plots at the University of Vermont, Jericho Research Forest.

Experimental Treatments

1. Uneven-aged Treatments

The first two treatments are 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 of 1.3. This results in increased retention of larger trees and a shift in basal area to larger size classes, although substantially less so than for the third set of treatments. The size of individual group-selection cuts (0.05 ha) is based on previous research describing the average scale of fine-scale natural disturbances in New England (Seymour et al. 2002).

2. Structural Complexity Enhancement

The third set of treatments are intended to promote old-growth forest characteristics while also providing opportunities for timber harvest. Structural objectives include multi-layered canopies, elevated large snag and downed coarse woody debris (CWD) densities, variable horizontal density, and re-allocation of basal area to larger diameter classes. The later objective is achieved using an unconventional marking guide based on a rotated sigmoid target diameter distribution. The distribution 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 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 also promoted through crown release. Prescriptions for enhancing snag and downed woody debris volume and density are based on stand potential and literature-derived targets. On some units downed CWD is created by pulling trees over, rather than felling, to create pits and exposed root wads.

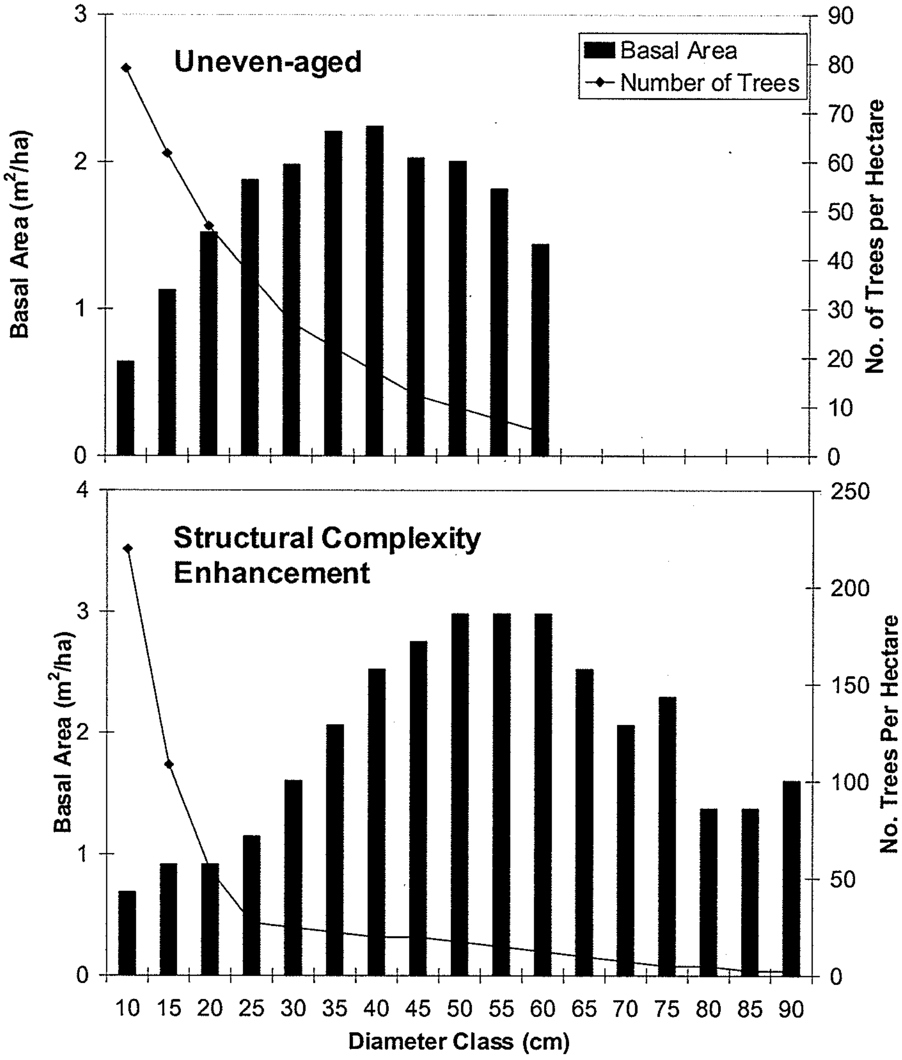


Figure 3. Target residual diameter and basal area distributions for single-tree selection and group-selection treatments (top) and structural complexity enhancement treatments (bottom). Note the desired future condition of basal area and stem density development into larger tree diameter classes in the later treatment.

3. Ecological Management Practices Shared by all Treatments

To demonstrate ecologically sensitive practices, all three experimental treatments promote a diversity of tree species and share retention of all dead trees, bear trees, and trees with special wildlife habitat characteristics, such as nesting or roosting cavities. All treatment units also included no-entry buffer zones around seeps, small forested wetlands, and streams. Prescriptions require retention of American beech exhibiting resistance to beech bark disease. All mature red spruce were retained as seed trees to encourage recolonization at mid elevations where this species was historically more abundant. Only pre-existing skid trails, logging roads, and landings were used for this study. These were relocated, surveyed using a GPS, and flagged prior to logging. We minimized soil impacts by logging on frozen ground and snow and forward piling slash on skid trails where possible. Loggers were required to keep diesel tanks, refuse, and sorting and loading operations away from streams. Skid trails, landings, and the main trucking road were decommissioned following logging (e.g. entrances barricaded, waterbars excavated, ruts recontoured and piled with slash, and landings and the trucking road seeded with conservation mix).

Sampling Design

There are five permanent sampling plots in each treatment unit. Plots are randomly placed, with 20 m minimum buffering from treatment unit edges, to meet statistical sampling requirements while ensuring even dispersion within each unit. Pre-determined plot centers were located in the field using an integrated GPS/laser range finder/digital electronic compass surveying system. Because plots are randomly placed, we have a minimum sample size of 5 data points per unit. Spatial independence among plots allows us to aggregate plots by treatment, resulting in larger sample sizes for certain purposes. In addition, our research sites are relatively homogeneous in stand age, management history, and species composition, resulting in low statistical variability between plots and more robust estimates of mean responses. Statistical rigor is increased further for variables sub-sampled within the 13 quadrats nested within each permanent plot.

Permanent plots incorporate several nested square plots and transects (Figure 4). These are used for annual sampling (pre and post-harvest) of overstory structure and species composition, tree regeneration, growth, and mortality rates, understory plant communities, wildlife habitat characteristics, and forest health. Wildlife surveys and soil sampling conducted by collaborating researchers are nested within the permanent plot system. Leaf area index is measured at plot center using a Licor 2000 Leaf Area Index Meter; hemispheric photographs of canopy architecture are taken there as well.

Plot design and the corresponding attributes sampled are shown in Figure 4. Nested square plots are 0.1 ha, 0.02 ha, and 1 m^2 in size. In the 0.1 ha. plot, all live and dead trees > 5 cm dbh and > 1.37 m tall are permanently tagged, measured, and recorded by species, diameter, height, and decay stage (snags only). Tree heights, height to crown base, and crown width (2 radii) on each tagged tree are measured using an Impulse 200 laser range finder. Assessments of tree health include coding of crown and bole condition, presence of disease and disturbance indicators, and presence of natural excavations and cavities. Additional forest health indicators assessed include crown dieback, crown density, and foliage transparency, which are estimated by percentage class for all dominant canopy trees. Beech bark disease (*Nectria coccinea* var. *faginata*) is assessed using a three class system developed for this project: BBD0 = no visible beech bark disease; BBD1 = light beech scale insect (*Cryptococcus fagisuga*) infestation; BBD2 = heavy scale insect infestation, but no *Nectria* fungal infection apparent; and BBD3 = *Nectria* infection. The cross sectional area of canopy gaps within the 0.1 ha plots is surveyed using the integrated system. Density and volume of tip-up mounds are measured within this plot size.

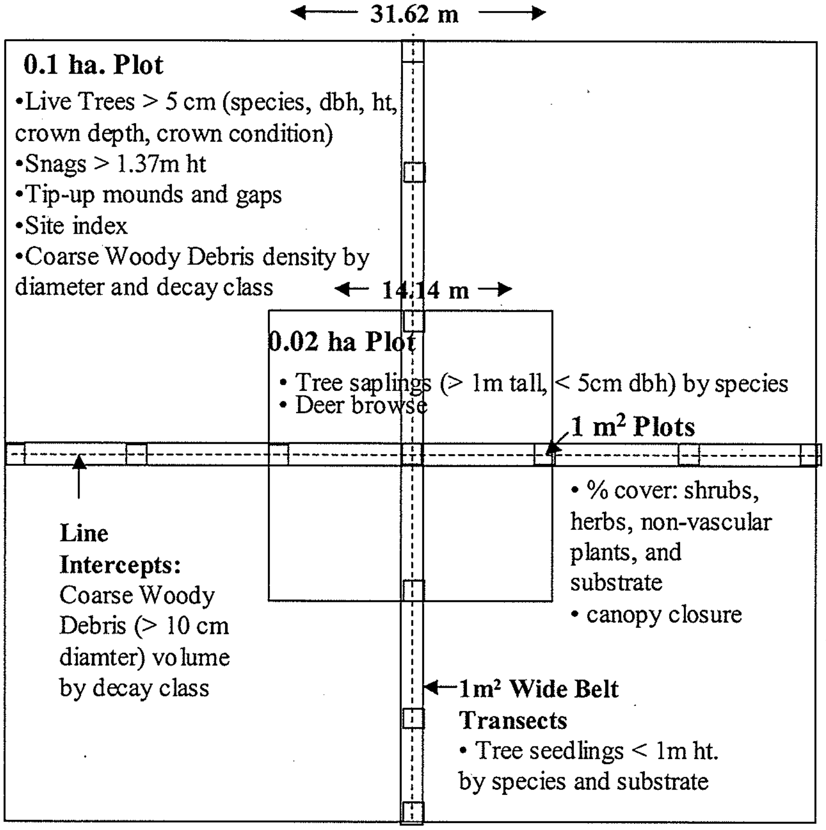


Figure 4. Design and layout of permanent sampling plots

There are thirteen m^2 quadrats used for estimating percent cover of all substrates (mineral soil, fine litter, rock, and coarse woody debris), understory plants by species (vascular and non-vascular plants), lichens, and above-ground fungal fruiting bodies. Canopy closure is measured at the center point of each quadrat using a spherical densitometer; litter layer depth is also measured at these points. The 0.02 ha. plot is used for tallying saplings (by species) that are > 1 m tall but < 5 cm dbh. Evidence of deer browse is also recorded by stem. Coarse woody debris (downed logs > 10 cm diameter at intercept) volume by decay class (1-5) is estimated using a line intercept method. Coarse woody debris densities are measured with the 0.1 ha plot. Tree seedlings (regeneration < 1 m height) are tallied by species within two belt transects that are each 1 m wide and 31.62 m long.

The center point of each plot unit is mapped to within 1 - 30 cm horizontal precision using the GPS. Plot unit center points and the position of understory quadrats and line transects are permanently monumented. Two dominant canopy trees are cored at breast height to allow subsequent laboratory determination of tree age and site index. Data are collected on slope, aspect, topographic position, and shape of topographic cross section.

Vegetation Data Analysis

Data are entered into the Northeast Decision Model (NED) (Simpson et al. 1996) and MS Excel and MS Access databases. Stand inventory metrics are generated in NED, with summary data exported to NED-SIPS for growth and yield and stand development simulation modeling. A Before/After/Control Experiment (BACE) methodology is used to structure many of the analyses. Effects are analyzed using statistical analyses of sample data and stand development modeling using the USDA Forest Service's Forest Vegetation Simulator (northeastern variant) and Stand Visualization System (SVS). Simulation modeling generates developmental scenarios for different treatments, allowing comparison of structural development as well growth, yield, and potential revenue associated with future logging entries. Stand development modeling allows sample sizes per treatment to be further increased via cross-application of simulated treatments. For instance, applying simulated SCE treatments to each of the single-tree selection units, and vice versa, doubles sample sizes for certain purposes.

Analyses to date have focused on overstory structure. Analyses of understory plant communities, tree regeneration, coarse woody debris, and other vegetational response variables is on-going. Statistical analyses are run in Excel and S-Plus. These include tests of means (e.g. *T*-tests), tests of variance (e.g. ANOVA, *F*-tests, etc.), multiple regression modeling, and multivariate analyses. To determine whether SCE shifted diameter distributions towards the target rotated sigmoid form, pre- and post-harvest and target distributions were log transformed. Log transformation enhances sigmoidal tendencies (Leak 2002). Residual distributions were smoothed using a Friedman smoothing run in S-Plus. Kolmogorov-Smirnov two-sample goodness of fit tests (Zar 1996) were used to test for statistically significant differences between transformed residual and target cumulative frequency distributions.

Project Schedule and Progress

The FEMDP was initiated in June 2001. We have completed two years of pre-treatment project development, stakeholder input assessment (i.e. workshops), site preparation and layout (i.e. unit boundary surveying and marking; skid trail marking), prescription design, permanent plot establishment, and data collection. Experimental manipulations (i.e. logging) were conducted in winter (Jan.-February) of 2003. We have completed one year of post-treatment data collection. A second season of post-treatment data collection (summer 2004) is on-going as of the writing of this report. Additional years of post-treatment data collection are planned pending funding.

Our efforts to date have focused on FEMDP implementation, including the necessary pre-treatment planning, stakeholder involvement, site preparation and marking, treatment, and initiation of post-treatment data collection. The project is now entering Phase Two, which focuses on analysis of treatment effects. Thus, research results currently available are preliminary only. With the second season of post-treatment data collection now underway, initiation of predictive modeling and statistical analyses of treatment effects are planned for 2004-2005 and following years.

RESULTS

Timber Harvesting Implications

As a demonstration project, FEMDP is producing information on the feasibility, operational requirements and harvesting implications of the treatments employed. Of particular note in this regard is the comparison of alternate diameter distributions as the basis for harvesting prescriptions. A key feasibility question has been whether the SCE prescription would result in harvest quantities and stem sizes that were sufficient to both provide merchantable material and achieve structural enhancement objectives (e.g. crown release, snags, and downed logs). There was uncertainty because the target SCE diameter distribution – indicative of old-growth structure – was applied to stands with substantially lower basal area and smaller tree sizes than the desired future condition used to generate the target distribution.

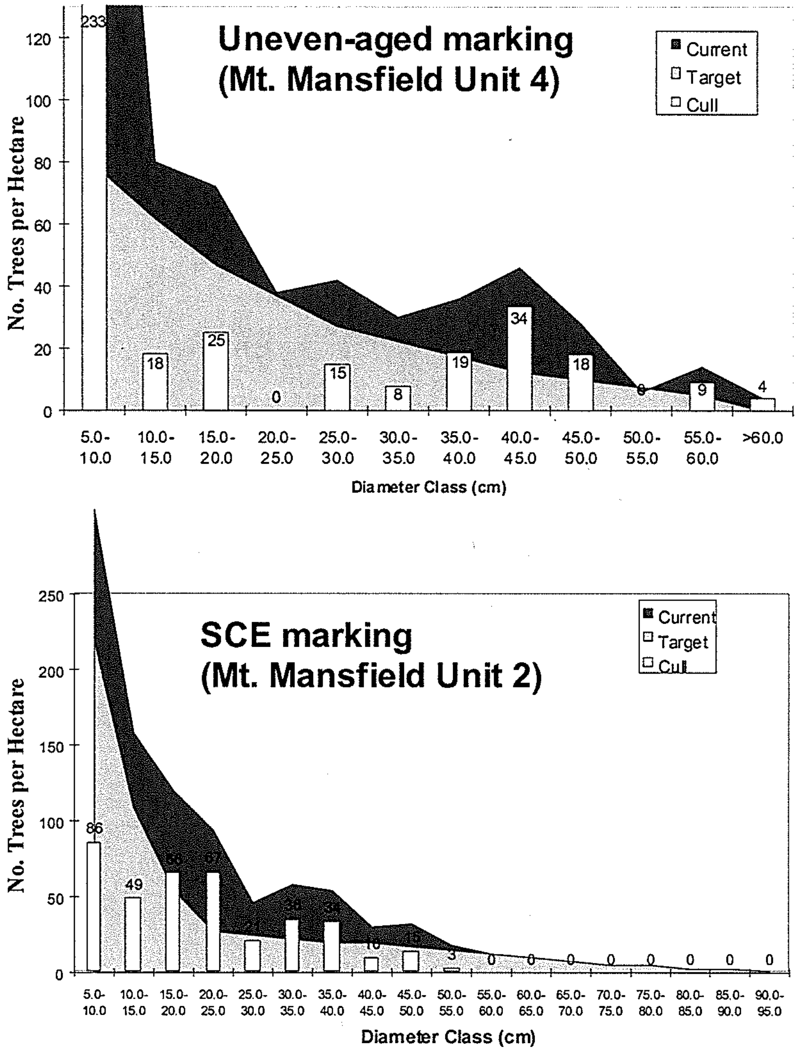


Figure 5. Marking results for one of the uneven-aged units (above) and one of the structural complexity enhancement units (below). Numbers above bars are the quantities of trees felled (harvested trees plus trees converted to CWD) by size class. Note the concentration of merchantable harvest trees in the mid-diameter classes and the release of large trees in the structural complexity treatment, versus the harvest of all trees over a maximum diameter limit (60 cm) in the uneven-aged treatments.

Figure 5 shows the timber harvest levels resulting from superimposing target diameter distributions on pre-harvest diameter distributions for one uneven-aged unit and one SCE unit. There are pronounced differences between the two. The uneven-aged treatments resulted in higher harvesting levels, particularly in the larger diameter ranges. All trees greater than the maximum diameter limit (60 cm) were harvested, which produced larger volumes of saw timber. In contrast, the SCE treatment – having no maximum diameter limit and an alternative target diameter distribution – concentrated merchantable timber harvesting in medium sized trees. Because medium diameter trees have a higher ratio of sapwood to heartwood, this resulted in proportionately higher removals of high quality sawtimber and veneer logs. Most large trees were retained in the SCE treatments, and a portion of those were crown released. High densities of stems were retained in both the small and medium size classes; a result similar to the uneven-aged treatments. For both uneven-aged and SCE treatments, retention levels in small and medium sizes classes was adequate to ensure continued recruitment into merchantable size classes and sustainability of stand structure, growth, and yield (Solomon and Leak 1986; Leak et al. 1987).

By retaining and releasing larger trees, it is likely that the potential for recruitment into size classes not represented in the pre-harvest stand was maintained and even enhanced by SCE. This potential was impaired by the removal of large trees in the uneven-aged treatments. However, the uneven-aged treatments did maintain a wide range of tree sizes, multiple canopy layers, well-spaced medium to large trees (<60 cm dbh), and generally high levels of structure (see Table 2). Thus, both treatments resulted in stand structures capable of continued late-successional development, depending on the specifics of future stand entries.

Operationally, logging contractors implemented all treatments successfully and without difficulty. The primary operational constraints were weather and terrain related; they were not specific to treatment. Uneven-aged treatments were the most time consuming because a) harvest volumes were larger; and b) some of the units were located on operationally challenging terrain. SCE prescriptions took the least time to log due to lower harvesting volumes. The SCE treatments included three different tree markings (harvest, drop and leave, and girdle). Locating and properly treating individual stems consumed a relatively small amount of additional time per tree compared to the uneven-aged treatments. Operationally, uprooting trees to produce tip-up mounds proved far less challenging than anticipated. At the Mount Mansfield, a mechanized tree shear pushed even the largest trees over with ease. At the Jericho Research Forest, skidders easily pulled over trees using cables. Directional uprooting downslope was also successful as prescribed.

Residual Stand Structure

High levels of residual stand structure were maintained by all of the experimental treatments (Table 4). Target residual basal areas were achieved or exceeded by all treatments. Canopy closure was highest for SCE and lowest for single tree selection units. Whether future tree regeneration densities and species composition will correlate with these differences remains uncertain. Canopy closure, as expected, was most variable across group-selection units. Aggregate canopy closure remained high in group-selection unit because 70- 80% of each group-selection units was unlogged and thus maintained full pre-harvest structure. Stocking levels were maintained at or above the B line by all treatments. The objective of increasing the relative proportion of red spruce was achieved in units 4 and 5 (i.e. the units where mature red spruce were most abundant). Red spruce increased in relative abundance by 3% in each of those units due to marking protocol.

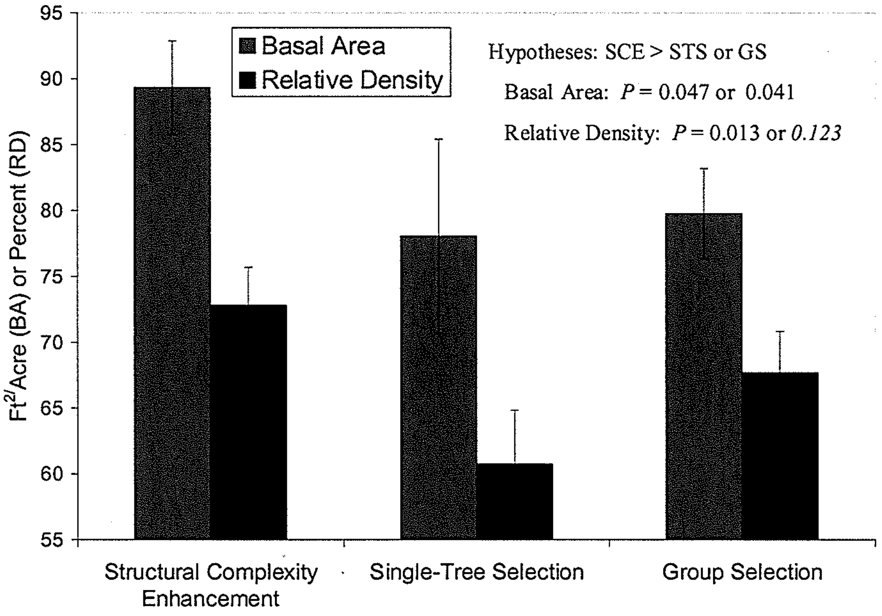
Table 4. Pre and post-harvest stand structure for each the eight experimental units at the Mount Mansfield study area. Values in italics are pre-harvest, whereas values in bold are post-harvest.

Unit	Treatment	Basal Area	Relative Density	Canopy Closure	% Conifers	Average dbh	Medial dbh	Quadratic Mean Diameter
1	Control	*143.4*	*116*	*100%*	*0%*	*7.45*	*16.49*	*9.68*
		143.4	**116**	**100%**	**0%**	**7.45**	**16.49**	**9.68**
2	Structural Complexity Enhancement	*125.2*	*102.8*	*95%*	*0%*	*5.99*	*14.65*	*7.89*
		88.9	**72.1**	**72%**	**0%**	**6.11**	**14.98**	**7.99**
3	Structural Complexity Enhancement	*105.3*	*89.7*	*89%*	*1%*	*5.4*	*12.99*	*7.03*
		87.7	**73.5**	**73%**	**1%**	**5.61**	**13.8**	**7.33**
4	Single-Tree Selection	*138*	*109.8*	*100%*	*4%*	*7.36*	*15.3*	*9.4*
		83.4	**65.3**	**65%**	**7%**	**7.66**	**14.63**	**9.44**
5	Single-Tree Selection	*130.4*	*103.7*	*97%*	*5%*	*7.23*	*14.59*	*9.05*
		81.9	**63.6**	**64%**	**8%**	**7.44**	**14.21**	**9.18**
6	Group-Selection	*110.9*	*95.2*	*94%*	*1%*	*5.12*	*13.28*	*6.87*
		82.5	**70.8**	**71%**	**1%**	**5.22**	**13.17**	**6.9**
7	Group-Selection	*107.8*	*92.8*	*91%*	*1%*	*5.4*	*12.33*	*6.95*
		70.4*	**59.8***	**60%***	**1%**	**5.5**	**12.4**	**7.1**
8	Control	*106.6*	*91.1*	*91%*	*1%*	*5.13*	*12.28*	*6.84*
		106.6	**91.1**	**91%**	**1%**	**5.13**	**12.28**	**6.84**

* Values are based on fixed-area permanent plots that were disproportionately logged. The unlogged matrix was inadequately sampled following harvest. Post-harvest values for Unit 7 are thus not representative of variability across the unit. This problem will be corrected using a full inventory of each group selection unit.

All treatments were successful at moving the units towards the desired diameter distributions. This is indicated by the slight increase in Quadratic Mean Diameter for all units (Table 2). This QMD increase is indicative of the reduction of small tree densities to target levels, which shifts basal area and growing space allocation to merchantable size classes. Medial diameter decreased in the uneven-aged units, however, because the largest trees were cut. In contrast, medial diameter increased in SCE units because large trees were retained and the target diameter distribution shifted the relative allocation of growing space from small to medium and large trees. This shift was of greater magnitude than for the uneven-aged treatments.

A significantly higher level of residual basal area was maintained by SCE (Figure 6) compared to either single tree selection ($P = 0.047$) or group selection ($P = 0.041$) units based on T tests assuming equal variance. Post-harvest relative density, a useful metric integrating basal area and stem 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 ($P = 0.123$). Equal variance assumptions in statistical tests were confirmed using *F* tests. There were no statistically significant differences ($\alpha = 0.05$) in variance within and among treatments using plots aggregated by treatment. This result held for both pre and post-harvest structure. Plots aggregated by treatment may be treated as independent samples without pseudoreplication. Spatial autocorrelation (Ripley's *K*) tests will be performed to further support this conclusion. The variance test results were not robust for group selection units due to disproportionate logging (i.e. patch cutting) across permanent plots; this problem will be addressed by future inventories. Variation at scales smaller than 0.1 ha (plot size) has not yet been tested, but will be tested by spatial analyses using stem maps.



Hypotheses: SCE > STS or GS

Basal Area: $P = 0.047$ or 0.041

Relative Density: $P = 0.013$ or *0.123*

Figure 6. Statistical comparison of post-harvest basal area and relative density between treatments at the Mount Mansfield study area. *P* values are respective of the different comparisons: structural complexity enhancement (SCE) vs. single-tree selection (STS) and SCE vs. group-selection (GS).

Structural complexity enhancement (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 either SCE unit at Mount Mansfield based on the results of goodness of fit testing using log transformed diameter distributions (Figure 7). To formulate this test, it was necessary to create residual distributions using real data for smaller diameter classes (<70 cm dbh) and hypothetical (e.g. future potential) values for larger diameter classes (>70 cm dbh). The later borrowed values from the target distribution. This was appropriate because the pre-harvest stands were in deficit for the largest diameter classes, such that actual residual distributions could not be expected to include trees in those classes. Statistical tests, therefore, evaluated a research question of whether residual distributions achieved that portion of the target distribution possible given the pre-harvest structure. SCE was successful in this regard (Figure 7). 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 based on the results.

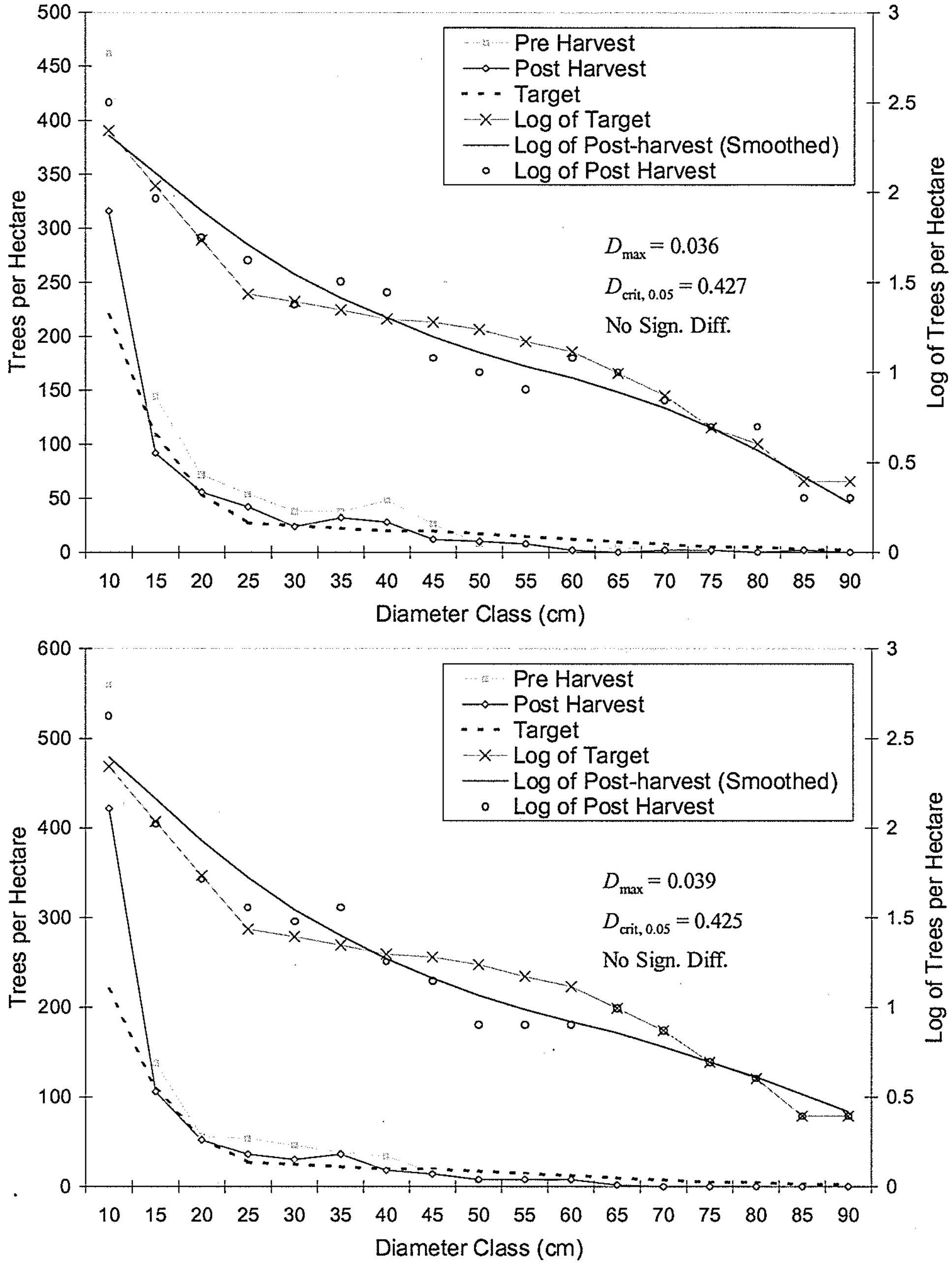


Figure 7. Pre-harvest, post-harvest, and target diameter distributions for structural complexity enhancement Unit 2 (above) and Unit 3 (below) at Mount Mansfield. Log transformed post-harvest and target distributions are compared (top portion of graphs) using the Kolmogorov-Smirnov two-sample goodness of fit test. There were no statistically significant differences. Thus, the post-harvest distributions achieved the target rotated sigmoid distribution.

Structural Modeling

Modeling using the USDA Forest Service's Stand Visualization System has focused to date on "before and after" evaluations of treatment effects, contrasting SCE with single-tree selection. Pictorial depictions of stand structure are generated in SVS using stem maps, detailed structural measurements (e.g. tree height, height to crown base, and average crown width) taken on every tagged trees (> 5 cm dbh), and CWD data. These representations are thus spatially and structurally explicit (Figure 8).

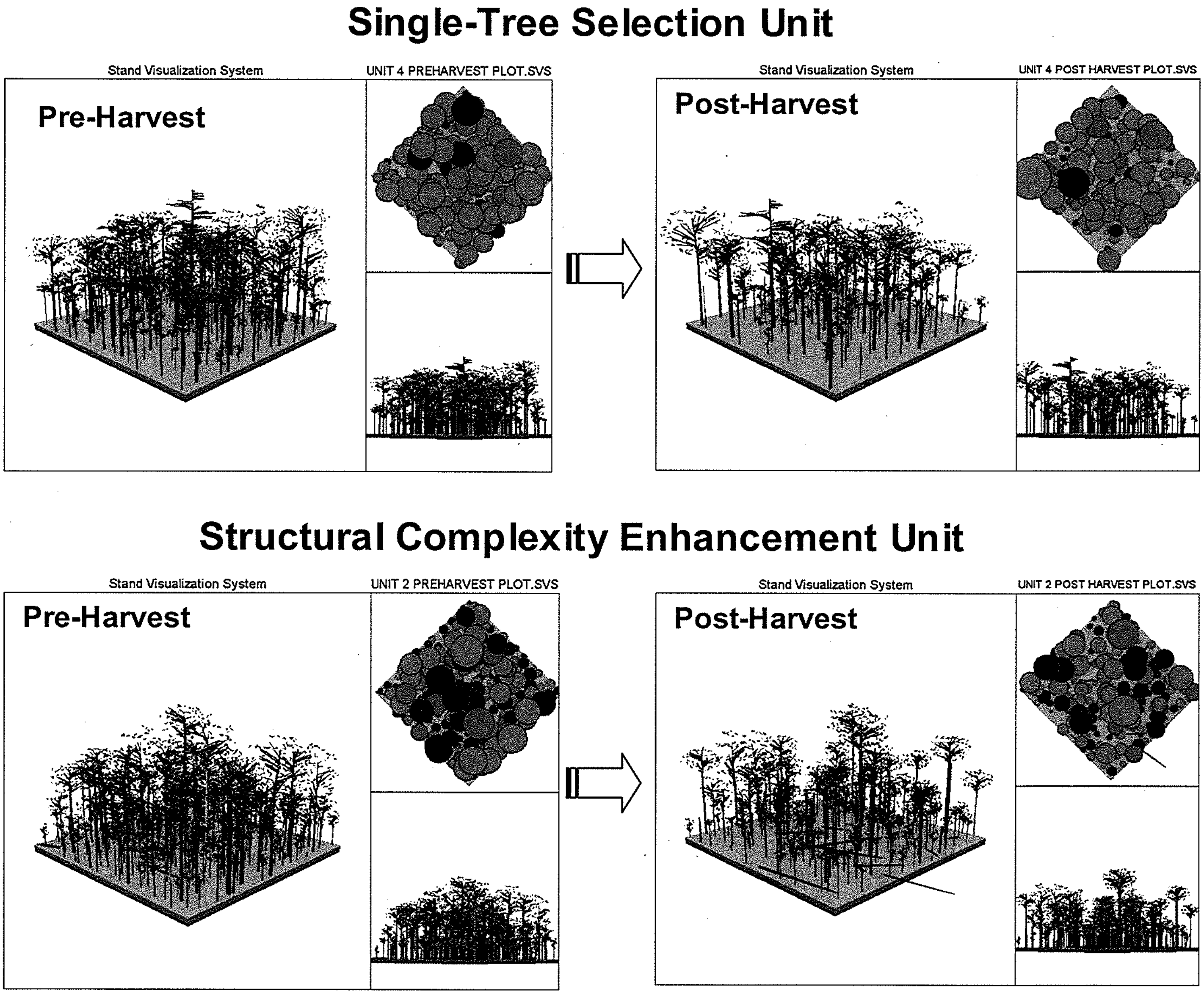


Figure 8. Output of SVS modeling contrasting single-tree selection Unit 4 (above) and SCE Unit 2 (below) at the Mount Mansfield study area. Shown are images of pre- and post-harvest stand structure for 1 ha. blocks. Note the high degree of post-harvest structure (e.g. basal area and stem density), canopy closure, canopy layering (i.e. vertical complexity), and downed CWD densities in the SCE unit. Note the similar, though somewhat lesser, effects on canopy structure for the single-tree selection unit. Both approaches maintained a high degree of canopy cover and residual overstory structure.

Visual outputs and the corresponding quantitative metrics (Figure 9) generated by SVS illustrate the high degree of canopt cover and structural complexity maintained by both SCE and single-tree selection trees. However, there are significant differences. SCE resulted in large increases in downed woody debris volumes and densities. Post-harvest canopy closure (as estimated by SVS) was also slightly greater after SCE (75%) than after the single-tree selection (71%). Both approaches maintained significant levels of crown volume across a full vertical spectrum, from forest floor to top of canopy (Figure 9, middle). Residual diameter distributions in the SCE units extend above the maximum diameter retained in single-tree selection units (Figure 9, top). However, canopy height actually decreased in SCE unit 2 due to the removal of a few, diseased tall trees due to crown release of the largest diameter, most vigorous canopy dominants (Figure 9, middle right). Both approaches maintained height and diameter distributions capable of sustaining vertical recruitment and bole and height growth.

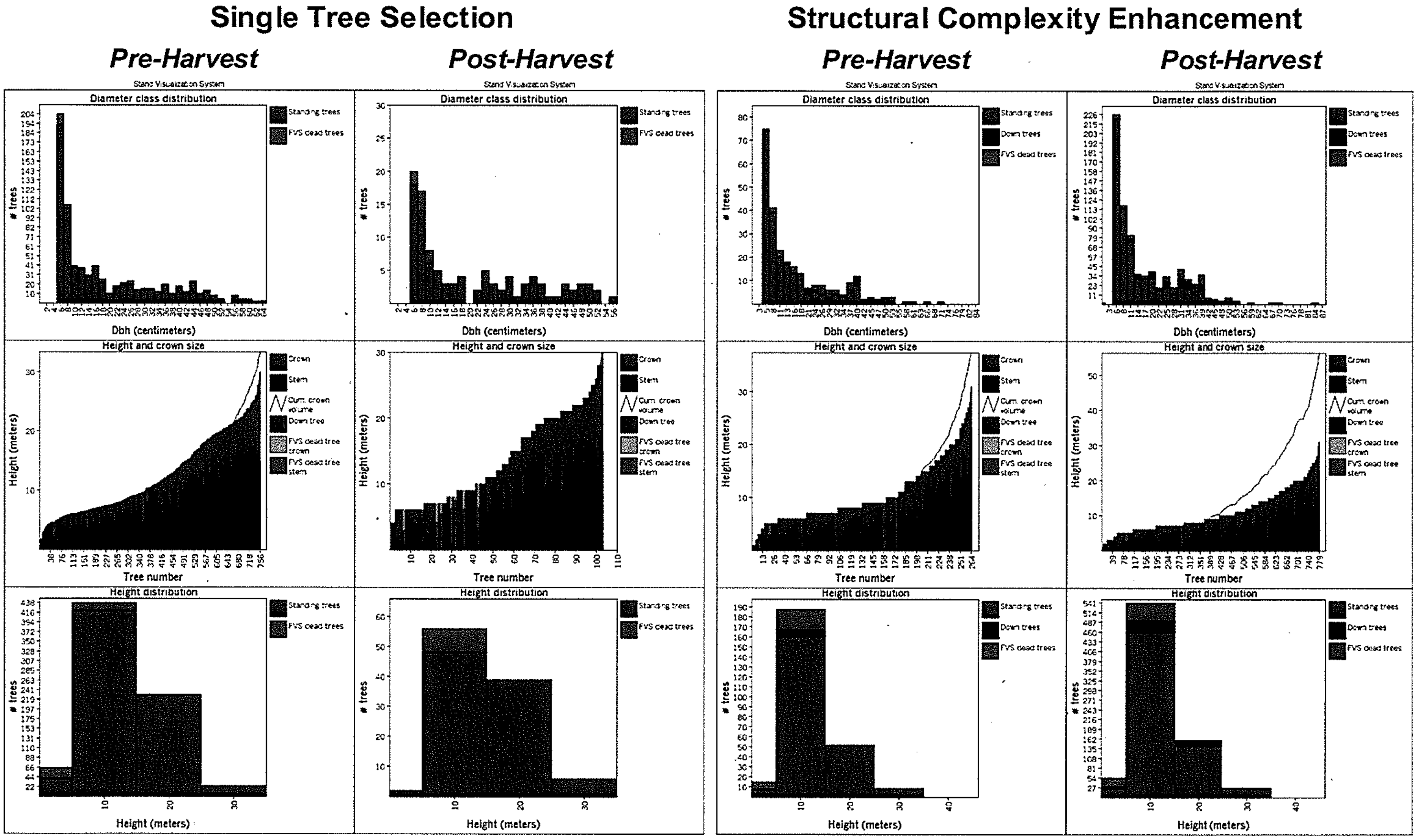


Figure 9. Quantitative output of SVS structural modeling for one single-tree selection unit (left) and one SCE unit (right) at the Mount Mansfield study area. Pre- and post-harvest distributions for selected metrics are presented.

The next step will be to use predictive simulation and growth and yield modeling to estimate the long-term implications of subtle differences between treatment effects. Preliminary runs in NED-SIPS using post-harvest data suggest that SCE will result in higher basal areas, compared to other treatments, after 50 years. The effects of horizontal structure, such as variations in stem density created by crown release thinning, on stand development will be of particular interest. Spatially explicit simulation modeling incorporating coordinate data for individual trees (Figure 10) will be used to capture these effects.

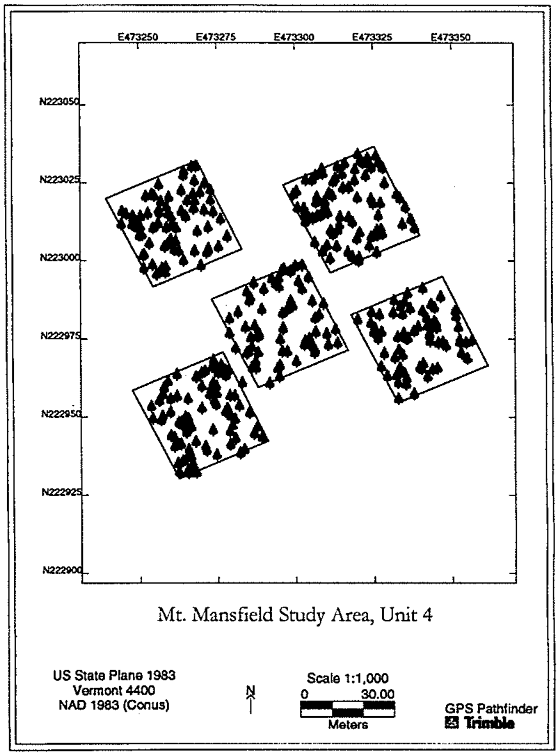


Figure 10. Pre-harvest stem map for one treatment unit at the Mount Mansfield study area.

COARSE WOODY DEBRIS ENHANCEMENT

Structural complexity enhancement (SCE) prescriptions resulted in substantially elevated densities and volumes of both downed coarse woody debris and standing snags (Figure 11).

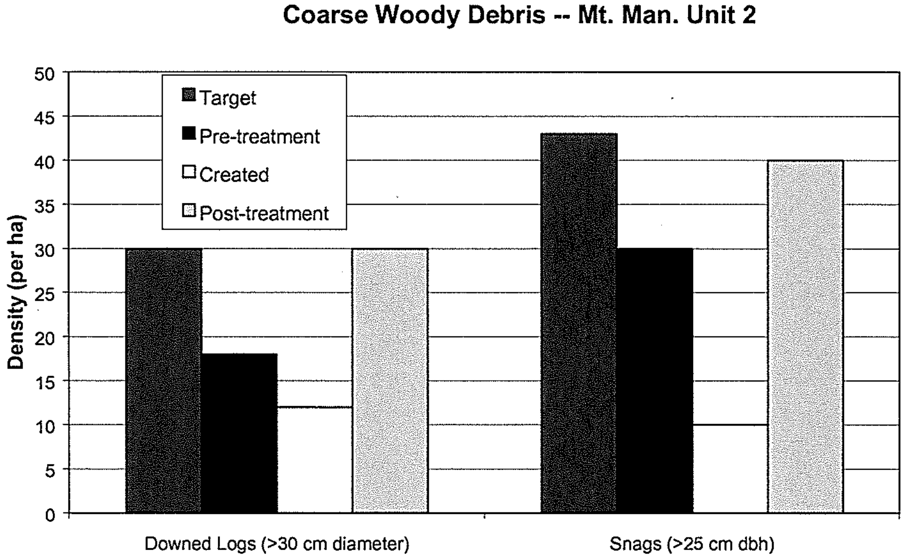


Figure 11. Target, pretreatment, and post-treatment CWD densities for one SCE unit at the Mt. Mansfield study area. Note that the number of logs or snags created is the difference between target and pretreatment density.

Figure 12. Tip-up mound and pit formed by pushing a tree over on Mt. Mansfield. Note the ski pole (center) shown for scale. Even relatively small or medium sized trees formed large root wads when uprooted.

The structural complexity enhancement treatments increased coarse woody debris 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. 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. Pulling trees over was successful at creating large exposed root wads and vernal-pool forming pits (Figure 12). In all but one case, trees pulled or pushed over uprooted fully, the only exception being a stem that snapped.

CROWN RELEASE AND VERTICAL DEVELOPMENT

Marking guides were used successfully to crown release 45 dominant trees per ha. on average in SCE units (Figure 13). This is likely to accelerate growth rates in dominant canopy 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 (3 or 4 sided), rather than partially (2 sided), crown released (Figure 14). Crown release also resulted in spatial aggregations of harvested trees, thereby increasing horizontal structural complexity, such as canopy openings and variable tree densities. Elevated light availability associated with this effect is predicted to promote vertical complexity (or canopy layering) through release and regeneration effects. Thus, it is likely that foliage density in the emergent and lower canopy layers will increase over time.

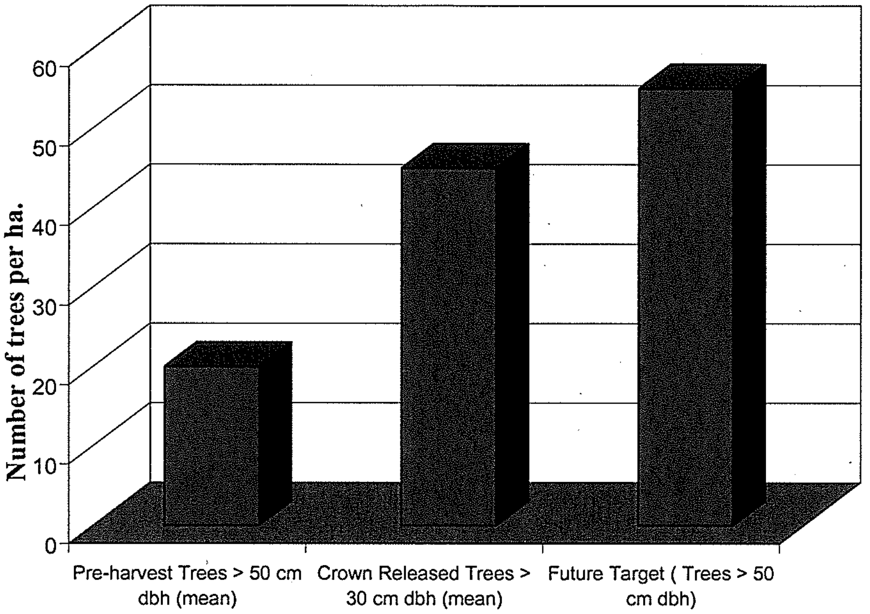


Figure 13. Mean number of trees crown released in the structural complexity enhancement units compared to pre-harvest. These are compared to target densities of large trees (>50 cm dbh) derived from reference old-growth stands described by previous studies. Note that more trees were released than the difference between target and pre-harvest densities. This was prescribed in order to compensate for expected mortality.

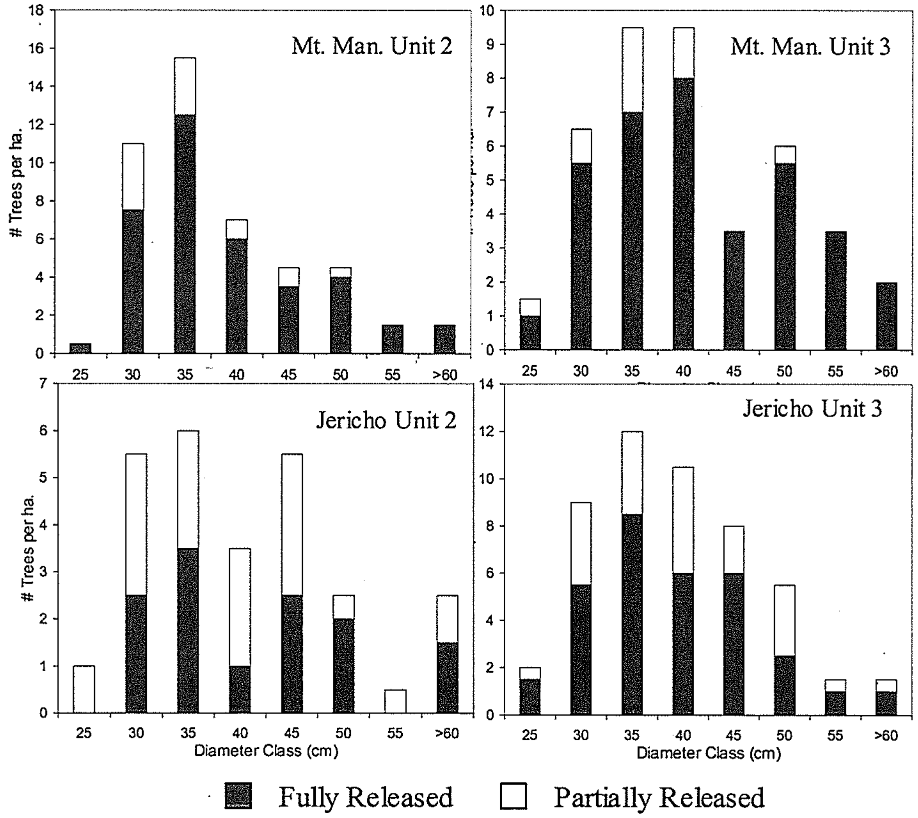


Figure 5. Crown release distributions by diameter class and degree of release (full vs. partial) for structural complexity units at the Mount Mansfield and Jericho Research Forest study areas.

The potential for continued vertical development (e.g. vertical differentiation of foliage) in all treatment units will be monitored using a foliage height diversity index (FHDI) and other metrics. To calculate FHDI, a program was created in MS Excel that calculates the vertical area occupied by individual tree crowns. Individual crown occupancies within increments of 1 m along a vertical gradient are pooled for each plot, with individual tree contributions weighted by their respective basal area. A proportion is then calculated for each strata representing its share of the stand's total foliage (Figure 15). These are aggregated to the unit level, allowing variance to be estimated. Finally, the foliage height diversity index is calculated from the pooled data based on the formula for the Shannon-Wiener Diversity Index.

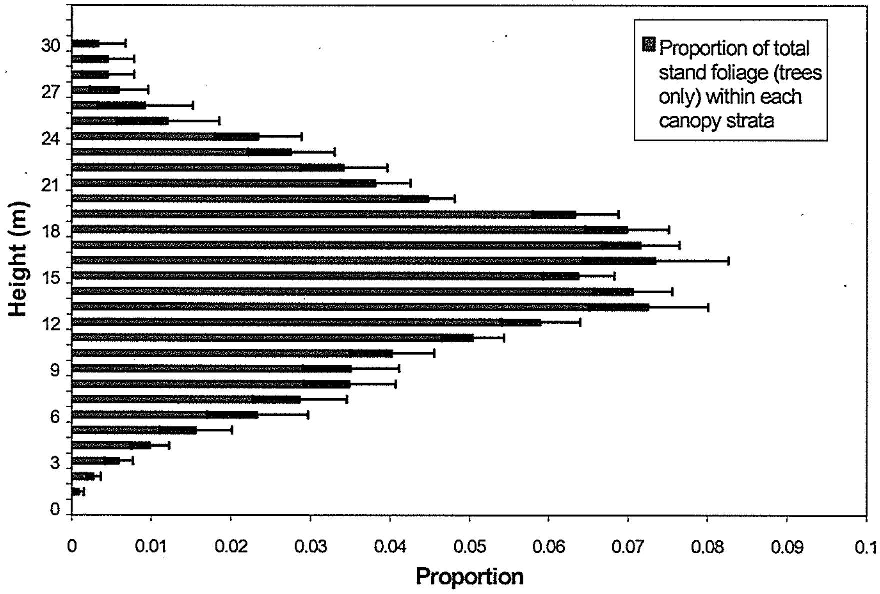


Figure 15. Pre-treatment vertical distribution of foliage (occupancy by tree crowns) as a proportion of total canopy structure within one structural complexity enhancement unit.

DISCUSSION

The FEMDP is helping forest managers evaluate the benefits, tradeoffs, and feasibility of structure-based silvicultural systems. The research implications are most relevant where management objectives include biological diversity and ecosystem functions associated with the structural conditions found in late-successional northern hardwoods. Based on preliminary analyses, silvicultural techniques can be used effectively to promote old-growth characteristics while also providing opportunities for low-intensity timber harvest. Both the uneven-aged and structural complexity enhancement (SCE) systems tested maintain high levels of post-harvest structure and canopy cover. However, SCE maintains or enhances CWD, canopy layering, and other structural attributes to a greater degree. Long-term stand development implications have yet to be explored, although we predict that the crown release and alternative diameter distribution prescriptions employed in SCE will accelerate rates.

Table 5. Potential applications of structural complexity enhancement

Application	# Entries	Late-Successional Structural Development
Old-growth promotion	One or possibly two entries	High
Riparian management	Single or multiple	Moderate to high
Timber emphasis	Multiple	Low to moderate

If our predictions are supported, then SCE would have a variety of useful applications, ranging from old-growth restoration, to riparian management, to low-intensity timber management and late-successional wildlife habitat enhancement (Table 5). Depending on the specific application, the SCE system tested by the FEMDP 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. Others elements might be set aside 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. Protected areas managers, 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.

The conclusion evident from our results is that forest managers have flexibility in managing for wide range of structural characteristics and associated ecosystem functions. Uneven-aged systems provide some but not all of these 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. Unconventional prescriptive diameter distributions, such as the rotated sigmoid, are another alternative for retaining high levels of post-harvest structure and for promoting accelerated stand development. The FEMDP will continue to explore a range of structure-based silvicultural options as one element of sustainable forest ecosystem management.

PRODUCTS AND INFORMATION TRANSFER: 2001-2004

Outreach

There has been tremendous interest in the FEMDP within Vermont, the Northeast, and nationally. Project investigators have been invited to present the project at over 14 conferences, workshops, and meetings to date. These have addressed a wide range of user groups, including scientists, federal and state natural resource personnel, professional foresters, and both industrial and small private non-industrial timberland owners. In addition, tours of the research sites have involved U.S Forest Service scientists, county and state foresters, and several undergraduate and graduate classes at the University of Vermont. A full list of FEMPD professional and scientific presentations is provided below:

Keeton, W.S. (Accepted). Managing for old-growth structure in northern hardwood forests. Invited presentation to the 6th Eastern Old-growth Conference: moving toward sustainable forestry, lessons from old-growth forests. September 23-26, 2004, Moultonborough, NH.

Keeton, W.S. (Accepted). Managing for old-growth structure in northern hardwood forests: experimental test of a new silvicultural system. Balancing ecosystem values: innovative experiments for sustainable forestry, IUFRO International Workshop. August 15-10, 2004, Portland, OR.

Keeton, W.S. Incorporating natural disturbances into models of succession, ecological variability, and land classification. Invited presentation to the Conservation Biology Seminar Series, Univ. of Vermont, Rubenstein School of Environment and Natural Resources. April 6, 2004.

Keeton, W.S. Managing for old-growth forest structure in northern hardwood forests: experimental test of a new silvicultural system. Fourth North American Forest Ecology Conference, Corvallis, Oregon, June 2003.

Keeton, W.S. and D.R. Tobi. Vermont sustainable forest management demonstration project. Annual Meeting of the New England Society of American Foresters, April 2003, Burlington, VT.

Keeton, W.S. and D.R. Tobi. Vermont sustainable forest management demonstration project. Annual Meeting of the Vermont Monitoring Cooperative, April 21 2003, Burlington, VT.

Keeton, W.S. Structure-based forestry: balancing multiple objectives in managed stands. Invited presentation to the Green Mountain National Forest planning advisory group ("Blueberry Hill Group"). January 27th, 2004, Barre, VT.

Keeton, W.S. Managing for forest structure as an element of forest ecosystem health. Forest Health Symposium. April 8, 2003. White River Junction, VT. .

Keeton, W.S. Post-treatment results of the Vermont Forest Ecosystem Management Demonstration Project. Annual meeting of the Vermont Monitoring Cooperative. March 21, 2003. Burlington, Vermont.

Keeton, W.S. Conservation on working forests: adding tools to our forestry toolbag. Invited presentation to the Vermont Wildlife Forum. October 4th, 2002. Montpelier, VT.

Keeton, W.S.. Uneven-aged, multi-aged, or disturbance-based forestry: research on evolving silvicultural approaches. Invited presentation to the Vermont Agency of Natural Resources. March 25, 2002. Essex Junction, VT.

Keeton, W.S. Uneven-aged, multi-aged, or disturbance-based forestry: research on evolving silvicultural approaches. Invited presentation to the Vermont Consulting Foresters Association. May 2, 2002. Ethan Allan Firing Range, Vermont.

Keeton, W.S.. The Vermont Forest Ecosystem Management Demonstration Project. A workshop conducted at the annual meeting of the Vermont Monitoring Cooperative. March 18, 2002. Burlington, Vermont.

Keeton, W.S. Old-growth forest restoration: how do we do it and is it a relevant conservation issue in New England? Invited presentation to the Conservation Biology Seminar Series, Univ. of Vermont, School of Natural Resources. October 24th, 2002.

Keeton, W.S. Playing god with ecological succession: the intersection of ecosystem science and sustainable forestry. Invited presentation to the University of Vermont, Marvin Lecture Series. January 2002, Burlington, VT.

Keeton, W.S. , A.M. Strong, D.R. Tobi, and S. Wilmot. Experimental test of structural complexity enhancement in northern hardwood-hemlock forests. The Forest Information Exchange: Forest Structure – A Multi-Layered Conversation. October 25, 2001, Orono, Maine.

Keeton, W.S. The once and future forest in New England: history, variability, and future uncertainty. Invited presentation to the National Forest Planning Meeting, Sponsored by The Wilderness Society and USDA Forest Service. February 24, 2001. Fairlee, VT.

Publications

Keeton, W.S. 2004. Managing for old-growth forest structure in northern hardwood forest. *In:* Balancing ecosystem values: innovative experiments for sustainable forestry. Proceedings of the IUFRO International Workshop, August 15-10, 2004, Portland, OR.. USDA Forest Service General Technical Report (Accepted).

Keeton, W.S. 2003. Managing for old-growth forest structure in northern hardwood forests: experimental test of a new silvicultural system (Abstract only). *In:* Proceedings of the Fourth North American Forest Ecology Conference, Corvallis, Oregon, June 2003. Oregon State University Press, Corvalis, OR.

Keeton, W.S., A.M. Strong, D.R. Tobi, and S. Wilmot. 2001. Experimental test of structural complexity enhancement in northern hardwood-hemlock forests. Pages 33-40 in: J.M. Hagan (ed.). Forest Structure: A Multi-Layered Conversation. Proceedings of the Forest Information Exchange, October 25, 2001, Orono, Maine. Manomet Center for Conservation Sciences, Brunswick, ME.

LITERATURE CITED

Aplet, G.H. and W.S. Keeton. 1999. Application of historical range of variability concepts to biodiversity conservation. Pages 71-86 in: R. Baydack, H. Campa, and J. Haufler (eds.). Practical Approaches to the Conservation of Biological Diversity. Island Press, Washington, D.C.

Buongiorno, J., S. Dahir, H.C. Lu, and C.R. Lin. 1994. Tree size diversity and economic returns in uneven-aged forest stands. Forest Science 40:83-103.

Cogbill, C.V. 2000. Vegetation of the presettlement forests of northern New England and New York. Rhodora 102:250-276.

Foster, D.R. 1992. Land-use history (1730-1990) and vegetation dynamics in central New England, USA. Journal of Ecology 80:753-772.

Foster, D.R., G. Moskin, and B. Slater. 1998. Land-use history as long-term broad scale disturbance: regional forest dynamics in central New England. Ecosystems 1:96-119.

Franklin, J.F., T.A. Spies, R. Van Pelt, A. Carey, D. Thornburgh, D.R. Berg, D. Lindenmayer, M. Harmon, W.S. Keeton, D.C. Shaw, K. Bible, and J. Chen. 2002. Disturbances and the structural development of natural forest ecosystems with some implications for silviculture. Forest Ecology and Management 155:399-423.

Goodburn, J.M. and C.G. Lorimer. 1998. Cavity trees and coarse woody debris in old-growth and managed northern hardwood forests in Wisconsin and Michigan. Canadian Journal of Forest Research 28:427-438.

Goodburn, J.M. and C.G. Lorimer 1999. Population structure in old-growth and managed northern hardwoods: an examination of the balanced diameter distribution concept. Forest Ecology and Management 118: 11-29.

Gore, J.A. and W.A. Patterson. 1985. Mass of downed wood in northern hardwood forests in New Hampshire: potential effects of forest management. Canadian Journal of Forest Research 16:335-339.

Haney, J.C. and C.P. Schaadt. 1996. Functional roles of eastern old-growth in promoting forest bird diversity. Pages 76-88 in: M.B.Davis. (ed.). Eastern Old-Growth Forests: Prospects for Rediscovery and Recovery. Island Press, Washington, D.C. 383 pp.

Keeton, W.S., A.M. Strong, D.R. Tobi, and S. Wilmot. 2001. Experimental test of structural complexity enhancement in northern hardwood-hemlock forests. Pages 33-40 in: J.M. Hagan (ed.). Forest Structure: A Multi-Layered Conversation. Proceedings of the Forest Information Exchange, October 25, 2001, Orono, Maine. 78 pp.

Leak, W.B. 1996. Long-term structural change in uneven-aged northern hardwoods. Forest Science 42:160-165.

Leak, W.B. 2002. Origin of sigmoid diameter distributions. USDA Forest Service Research Paper NE-718.

Leak, W.B., D.S. Solomon, and P.S. DeBald. Silvicultural guide for northern hardwood types in the Northeast (revised). USDA Forest Service Research Paper NE-603. 36 pp.

McGee, G.G., D.J. Leopold, and R.D. Nyland. 1999. Structural characteristics of old-growth, maturing, and partially cut northern hardwood forests. Ecological Applications 9:1316-1329.

Mitchell, R.J., B.J. Palik, and M.L. Hunter. 2002. Natural disturbance as a guide to silviculture. Forest Ecology and Management 155:315-317.

Mladenoff, D.J. and J. Pastor. 1993. Sustainable forest ecosystems in the northern hardwood and conifer forest region: concepts and management. Pages 145-180 in: G.H. Aplet, N. Johnson, J.T. Olson, and V.A. Sample (eds.). Defining Sustainable Forestry. Island Press, Washington, DC 328 pp.

Niese, J.N. and T.F. Strong. 1992. Economic and tree diversity trade-offs in managed northern hardwoods. Canadian Journal of Forest Research 22:1807-1813.

Niese, J.N., T.F. Strong, and G.G. Erdmann. 1995. Forty years of alternative management practices in second-growth, pole-size northern hardwoods. II. Economic evaluation. Canadian Journal of Forest Research 25:1180-1188.

Nyland, R.D. 1998. Selection system in northern hardwoods. Journal of Forestry 96:18-21.

O'Hara, K.L. 1998. Silviculture for structural diversity: a new look at multi-aged systems. Journal of Forestry 96:4-10.

Seymour, R.S., A.S. White, and P.H. deMaynadier. 2002. Natural disturbance regimes in northeastern North America: evaluating silvicultural systems using natural scales and frequencies. Forest Ecology and Management 155:357-367.

Simpson, B T., R. P. Kollasch, M. J. Twery, T. M. Schuler. 1996. NED/SIPS User's manual - Northeast Decision Model Stand Inventory Processor and Simulator - Version 1.11. USDA Forest Service Gen. Tech. Rpt. NE-205.

Singer, M.T. and C.G. Lorimer. 1997. Crown release as a potential old-growth restoration approach in northern hardwoods. Canadian Journal of Forest Research 27:1222-1232.

Solomon, D.S. and W.B. Leak. 1986. Simulated yields for managed northern hardwood stands. USDA Forest Service Research Paper NE-578. 24 pp.

Trombulak, S.C. 1996. The restoration of old-growth: why and how. Pages 305-320 in: M.B.Davis. (ed.). Eastern Old-Growth Forests: Prospects for Rediscovery and Recovery. Island Press, Washington, D.C. 383 pp.

Tyrrell, L.E. and T.R. Crow. 1994a. Dynamics of dead wood in old-growth hemlock-hardwood forests of northern Wisconsin and northern Michigan. Canadian Journal of Forest Research 24:1672-1683.

Tyrrell, L.E. and T.R. Crow. 1994b. Structural characteristics of old-growth hemlock-hardwood forests in relation to stand age. Ecology 75:370-386.

Zar, J.H. 1996. Biostatistical Analysis (3rd ed.). Prentice Hall, Upper Saddle River, NJ. 662 pp. plus appendixes.