Proceedings of the International Conference: Ecologisation of
Economy as a Prerequisite for Sustainable Development.
© 2006. Ukrainian National Forestry University, L'viv, Ukraine.

BALANCING ECOLOGICAL AND ECONOMIC OBJECTIVES WHILE MANAGING FOR OLD-GROWTH FOREST CHARACTERISTICS

WILLIAM S. KEETON [1] AND AUSTIN R. TROY

Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405, USA

Abstract. Recent research in the United States and Canada has focused on sustainable forestry practices that maintain biological diversity and ecosystem functioning across managed forest landscapes. In the northern hardwood region this includes managing for old-growth forest structure, which is vastly under-represented relative to pre-European settlement conditions. One possibility is to modify uneven-aged silvicultural practices to more closely approximate fine-scale natural disturbance effects. The as yet untested hypothesis is that these approaches would result in accelerated rates of late-successional development and related ecological functions, while also providing economic returns from low-intensity timber harvests. We are testing this hypothesis using a variant of uneven-aged forestry, termed "Structural Complexity Enhancement (SCE)," that promotes old-growth structural characteristics. 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, U.S.A. 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 in SCE include multi-layered canopies, elevated large snag and downed log densities, variable horizontal density, and re-allocation of basal area to larger diameter classes. Data on operational expenses and revenue, sorted by treatment and product, were collected during and after logging operations. Expected net profits were evaluated under a number of different cost scenarios. Forest structure data have been collected over two years pretreatment and three years post-treatment. Fifty-year simulations of stand development were run using two forest development simulation models. There will be significant differences in stand development based on the simulation modeling. Late-successional structure will develop faster and to a greater degree under SCE. Large tree (>50 cm dbh) recruitment will be impaired under the conventional treatments, whereas recruitment will be accelerated under SCE. Siviculturalists have the flexibility to manage for structural complexity using unconventional silvicultural approaches. Under most conditions these will result in lower economic returns compared to more intensive harvesting practices. However, given acceptable site quality and market conditions, they will provide sufficient economic returns to either offset the cost of harvesting or generate a profit. Applications range from old-growth forest restoration to low intensity timber management.

Key words: sustainable forestry; forest economics; uneven-aged forestry, stand development, old-growth forests.

INTRODUCTION

Sustainable forestry practices across managed forest landscapes contribute to the maintenance of biological diversity and ecosystem functioning, for instance by providing connectivity between protected areas and unimpaired watershed processes. "Structure-" (Keeton 2005) or "natural disturbance-based" (Mitchell 2002, Seymour et al. 2002) silvicultural approaches provide alternatives for forest landscape management. Structure-based forestry focuses on the architecture of forest ecosystems at both stand-level and landscape-level spatial scales. Disturbance-based silviculture attempts to approximate the range of structural and compositional conditions associated with natural disturbance regimes. These approaches share the operational objective of managing for currently under-represented forest structures and age classes.

In the northern hardwood region of the northeastern United States and southeastern Canada a structure or disturbance-based approach would include managing for late-successional structure, which is vastly under-represented relative to pre-European settlement conditions (Cogbill 2000, Lorimer 2001, Lorimer and White 2003). An untested hypothesis is that silviculatural practices can

---

[1] Present address: University of Vermont, 343 Aiken Center, Burlington, VT, 05405, USA. Tel. +1 802 656 2518 Email. william.keeton@uvm.edu

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	• Modified single-tree selection timber harvest • Release advanced regeneration • Establish new tree cohort
Elevated large snag densities	• Girdling of selected medium to large sized, low vigor trees
Elevated downed woody debris densities and volume	• Felling or pulling over trees to create large downed logs and tip-up mounds
Variable horizontal density	• Harvested trees clustered around “crown release trees” • Variable density marking and harvest
Re-allocation of basal area to larger diameter classes	• Rotated sigmoid target diameter distribution • High target basal area (34 m^2/ha.) • Maximum target tree size set at 90 cm dbh
Accelerated growth in largest trees	• Full and partial crown release of largest, healthiest trees

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. We are testing this hypothesis using an approach, termed “Structural Complexity Enhancement (SCE), that promotes old-growth characteristics while also providing opportunities for low-intensity timber harvest (Table 1). SCE is compared against two conventional uneven-aged systems advocated regionally for sustainable forestry (Mladenoff and Pastor 1993, Nyland 1998). Conventional uneven-aged prescriptions employed in this study are modified to increase post-harvest structural retention. In addition, group-selection treatments are modified to approximate the average canopy opening size associated with fine-scale natural disturbance events in the northeastern United States, based on the findings of Seymour et al. (2002).

Alternative silvicultural approaches

Interest in structure-based silviculture has evolved from studies of old-growth northern hardwood and mixed hardwood-conifer forests. These have demonstrated the ecological significance of specific structural elements associated with late-successional and old-growth forests (e.g. Tyrell and Crow 1994b, Dahir and Lorimer 1996, McGee et al. 1999, Ziegler 2000). Availability of these structures can be highly limited in forests managed under conventional even and uneven-aged systems (Gore and Patterson 1985, 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 (Keeton et al. 2005). As a result, managing for old-growth structural characteristics, either in part or in full, is a proposed alternative silvicultural approach (Keddy and Drummond 1996, Lorimer and White 2003). While there has been much discussion of old-growth forest restoration in the theoretical literature (Trombulak 1996), there have been few experimental studies of relevant silvicultural methods for northern hardwood forests. Thus, it remains uncertain whether active restoration offers advantages over passive (or non-manipulative) restoration as means for recovering old-growth forest conditions. Our experimental test of SCE addresses this uncertainty.

The objectives of SCE include vertically differentiated canopies, elevated large dead tree and downed coarse woody debris (CWD) densities, variable horizontal density (including small gaps), and re-allocation of basal area to larger diameter classes (Table 1). 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 (O’Hara 1998), but their silvicultural utility has not been field tested. Sigmoidal form is one of several possible distributions in eastern U.S. 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 to larger trees. We predict that the rotated sigmoid distribution is sustainable in terms of recruitment, growth, and yield. If so, it would suggest that silviculturalists have greater flexibility in managing stand structure, biodiversity, and other ecosystem functions in the northern forest region than previously recognized.

Economic tradeoffs

Our on-going research is evaluating the economic tradeoffs among the structure-based systems tested. The objective is to determine the stand (timber volume and quality), site (accessibility and cost of harvesting operations) and market conditions necessary for structure-based systems to be economically viable and profitable. The economics of systems 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). For alternative silvicultural approaches to have appeal for landowners and forest managers, their operational and economic feasibility must be demonstrated. We are 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 a number of research questions. For instance, what are the economic tradeoffs involved with varying intensities of timber removal versus habitat enhancement? What is the economic viability of alternative silvicultural models under different scales of production? What is the level of economic uncertainty of these systems? How sensitive are returns to market prices of different forest products? And finally, what factors beyond stumpage volume, price, and interest rates affect economic feasibility and risk?

METHODS

Experimental design and data collection

The study is replicated at two mature, multi-aged, northern hardwood forests in the northern Green Mountain Range in Vermont, U.S.A. Dominant overstory species include *Acer saccharum* (sugar maple), *Betula alleghaniensis* (yellow birch), and *Fagus grandifolia* (American beech). There are co-dominant or minor components of *Tsuga canadensis* (eastern hemlock), *Acer rubrum* (red maple), *Picea rubens* (red spruce), and *Quercus rubra* (red oak) at some sites.

There are three experimental manipulations. The first two are conventional uneven-aged systems (single-tree selection and group-selection) modified to increase post-harvest structural retention and to represent best available practices. Prescriptions 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. Group-selection cutting patches are each approximately 0.05 ha in size. The third treatment is Structural Complexity Enhancement (SCE). The marking guide is 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. Accelerated growth in larger trees is promoted through full (4 or 3-sided) and partial (2-sided) crown release. Prescriptions for enhancing dead tree and downed woody debris volume and density are based on pre-harvest CWD volume and literature-derived targets. 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; the third (SCE) is replicated four times. Two un-manipulated control units are located at each of the two study areas. Treatment units are 2 ha in size and separated by 50 meter (min.) buffers. Treatments were randomly assigned. Experimental manipulations (i.e. logging) were conducted on frozen ground in winter 2003. Sample data were collected from five 0.1 ha permanent sampling plots randomly established in each treatment unit. Forest structure data, including leaf area index (LAI), detailed measurements of individual trees, and coarse woody debris (CWD) densities and volumes, have been collected over two years pretreatment and three years post-treatment. Plots were stem-mapped using an integrated laser range finder and digital electronic compass.

To track operational expenses loggers were required to file daily worksheets. These recorded hours worked, equipment use and repairs, number and type of loads, and work conditions. Harvested logs were separated into four product grades: saw logs, veneer logs, firewood, and chip wood. Logs were then segregated by treatment, transported, and tracked independently by unit through to scaling (valuation) at the processing mill. In this way harvest volumes and revenue could be tracked by treatment, species, size class, and grade or product.

Data analysis

Forest sample data were used as inputs for 3-dimensional modeling in the Stand Visualization System (SVS) (McGaughey 1997). The Northeast Decision Model (Twery et al. 2005) was used to generate stand structure metrics based on pre and post-harvest sample data. Structural metrics were analyzed using a before/after/control/impact statistical approach. For this purpose we used Tukey-tests, Analysis of Variance, and post-hoc Bonferroni or Least Significant Difference multiple comparisons. Fifty-year simulations of stand development were run using two models: the northeastern variant of the Forest Vegetation Simulator (FVS) and NE-TWIGS (Bush 1995). The FVS modeling structure is based on NE-TWIGS, which is an individual tree-based, distance-independent stand growth simulator. However, mortality and large-tree growth functions operate slightly differently in NE-FVS and calculations are made every ten years, rather on the annual time step employed in NE-TWIGS.

We ran simulations for individual experimental units and for both “no-treatment” (pre-harvest data) and “treatment” (post-harvest data) scenarios. Cumulative basal area increment (CBAI) was calculated for each simulation run at 5 year intervals. Projections were normalized on a unit by unit basis by calculating the differences between “no-treatment” and “treatment” 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 projected time series.

Economic data were entered into a Microsoft Access relational database. The series of linked tables includes hours worked by activity and treatment unit; receipts and quantity by product grade, type and load; number, size and destination of loads by treatment unit; costs per hour by equipment and personnel class, and added expenses. Operational expense and revenue data were used to quantify costs and net profits under each treatment for three cost scenarios designated as “non-profit,” “semi-profit,” and “for-profit.” The scenarios reflected the extent to which expenses not directly linked to harvesting, such as timber marking, would be accounted for as costs. Linear regression analysis was used to model relationships between receipts and pre-harvest timber volume. Revenue by treatment was also evaluated as a ratio relative to labor hours, since this was the greatest operational expense by at least one order of magnitude.

RESULTS

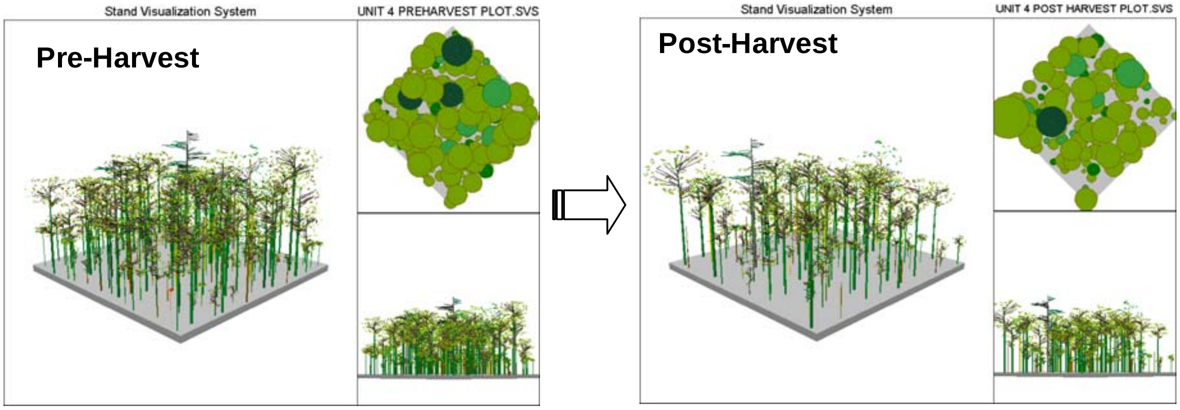
Residual stand structure

Visualizations generated in SVS illustrate the high degree of structural complexity maintained by both SCE and single-tree selection (figure 1). Post-harvest basal area, relative density, canopy closure, and LAI were significantly ($\alpha = 0.05$) higher under SCE compared to conventional treatments. Conventional treatments resulted in significantly lower aboveground biomass ($P = 0.014$), total basal area ($P = 0.003$), relative density ($P = 0.002$), and stem density ($P = 0.008$) in comparison to control units. SCE did not result in statistically significant contrasts with controls. Canopy closure was most variable across group-selection units. There were significant differences ($P < 0.001$) in LAI responses among treatments. Single-tree and group selection cuts reduced LAI by 19.8 and 29.9% respectively. LAI reductions were lowest in SCE units (9.4%), indicating high retention of 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 both group-selection and SCE, achieved in the later through variable density marking and clustered harvesting around crown-release trees. SCE shifted residual diameter distributions to a form statistically indistinguishable ($\alpha = 0.05$) from the target rotated sigmoid form.

Crown release and vertical development

Variable density timber harvesting was used successfully to crown release 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). Crown release also resulted in spatial aggregations of harvested trees, creating canopy openings and variable tree densities. Elevated light availability associated with this effect is likely to promote vertical differentiation of the canopy through release and regeneration effects.

Single-Tree Selection Unit



Structural Complexity Enhancement Unit

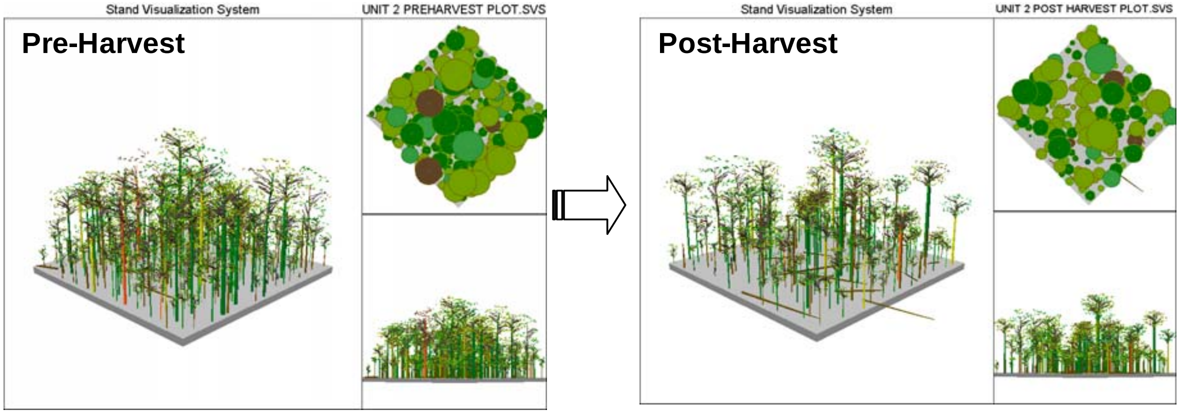


FIGURE 1. Output of the Stand Visualization System (SVS) contrasting a single-tree selection unit (above) and a Structural Complexity Enhancement (SCE) unit (below) at the Mount Mansfield study area. Shown are images of pre- and post-harvest stand structure for 1 ha. blocks. Shaded circles represent 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 for single-tree selection.

Coarse woody debris enhancement

SCE prescriptions resulted in substantially elevated densities and volumes of both downed coarse woody debris and standing snags (dead trees). The structural complexity enhancement treatments increased coarse woody debris (> 30 cm dbh) densities, on average, by 10 boles/ha for snags and 12 boles/ha for downed logs. Snags were created primarily by girdling diseased, dying, or poorly formed trees. Pulling trees over was successful in most cases at creating large exposed root wads and pits. There were statistically significant differences ($P = 0.002$) between treatments with respect to downed CWD recruitment. Post-harvest CWD (logs > 10 cm diameter) volumes were 140% higher on average than pre-harvest levels in SCE units; mean CWD volume increased 30% in conventional uneven-aged units due to residual slash.

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 (figure 2). This is 24 % (or 8 m^2/ha) higher than the mean predicted for the conventional uneven-aged units. Projected basal area for SCE also exceeds the mean predicted for control units by 13% (or 4.5 m^2/ha). Conventional units were projected to have basal areas still 12 % (or 3.6 m^2/ha) below the control units after 50 years of development. However, the difference among treatments is largely an artifact of the higher residual basal area left by SCE. The projections showed no significant differences in absolute growth rates between treatment scenarios. 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. However, when projected development is normalized against the null scenario (development expected with no treatment), the simulations indicate that conventional systems will increase cumulative basal area increment (CBAI) slightly more, although this difference was not statistically significant. Aboveground biomass production is accelerated 5.1% for SCE and 1.9% for conventional treatments compared to no treatment scenarios.

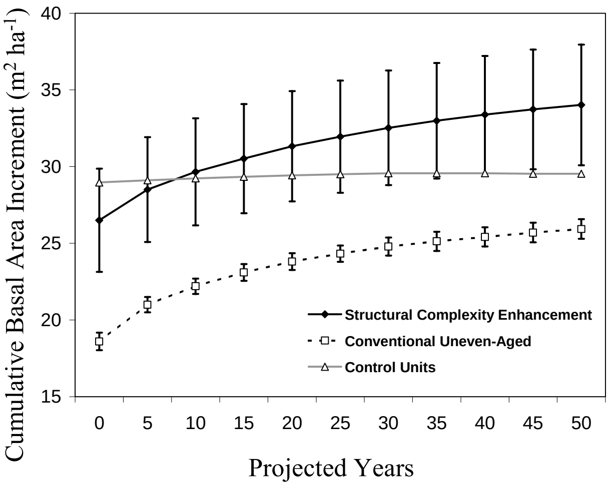


FIGURE 2. Results of stand development simulation modeling. Shown are 50 year projections of post-treatment cumulative basal area production (live trees only). Error bars are ±1 standard error of the mean.

Neither SCE nor conventional treatments resulted in projected basal area or biomass values that exceeded those projected for "no treatment" scenarios. However, basal area in SCE units recovered to within 89% of the no-treatment scenario, whereas conventional units recovered to within 77% on average. After 50 years SCE results in aboveground biomass that is 91.4% of that projected under no treatment, while the conventional treatments result in 79.1% of the no treatment potential. These differences were statistically significant ($\alpha = 0.05$).

SCE is projected to enhance rates of large tree recruitment over no treatment scenarios (figure 3). There will be an average of 5 more large trees (> 50 cm dbh) per ha than there would have been without treatment after 50 years in SCE units. There will be 10 fewer large trees/ha on average in the conventional units than would have developed in the absence of timber harvesting. Projections suggest that a rotated sigmoid diameter distribution will be sustained over 50 years in SCE units. The corresponding projected basal area distributions indicate significant reallocation of basal area and biomass into the largest size classes (e.g. > 50 cm dbh) for SCE.

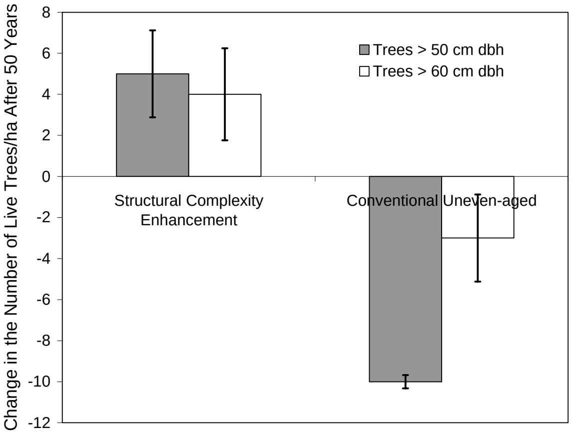


FIGURE 3. Projected change in large tree densities after 50 years. Values represent the difference between treatment and no treatment scenarios. Note the increased recruitment of large trees under SCE versus the impairment of large tree recruitment under the conventional uneven-aged treatments. Error bars are ±1 standard error of the mean.

Economic return

Profit margins were highly variable between units due to differences in site quality and treatment prescriptions. Pre-harvest timber volume (and associated surplus available for harvest) was strongly related to revenue for both SCE ($r^2 = 0.56$) and conventional treatments ($r^2 = 0.71$). Thus, site quality accounted for the most variability in harvest revenue among similarly treated units. Single-tree selection resulted in the highest net profits, but was also randomly assigned to units with the highest pre-treatment volumes and greater harvesting opportunities. Average revenue generated per ha. for this treatment was $4,150. Group-selection provided a moderate profit margin but, under a "for profit" scenario, incurred a deficit in one unit where pre-harvest volume was low. Group-selection generated an average revenue of $2,930 per ha. SCE revenues ranked lowest among the treatments, producing $1,710 per ha.

Net profits for SCE varied by treatment unit and cost scenario. Under a "for profit" scenario, net profits for SCE were only positive for sites with higher pre-treatment timber quality. If marking and incidental costs were not considered, SCE resulted in a net profit for all but one unit, where a $425/ha. deficit was incurred. Under favorable cost and site-quality (e.g. top two highest grossing units per treatment) scenarios, net profits per ha. for single-tree selection, group selection, and SCE were $1,550, $900, and $300 respectively. Since these margins include labor costs, they represent profits that would be returned to a landowner after logging contractors have been paid. Sensitivity analysis showed that reducing labor costs by even a small amount would result in profitability for marginal SCE units under all cost scenarios.

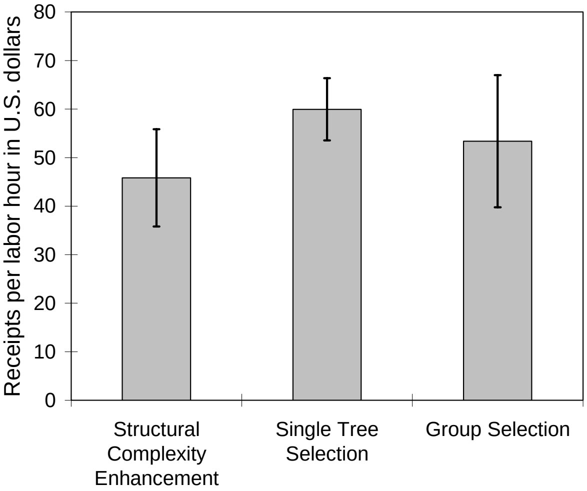


FIGURE 4. Mean ratio of before trucking receipts (in U.S. dollars) to labor hours for each of the three experimental treatments. Differences were not statistically significant (P> 0.05). Error bars are ±1 standard error of the mean.

Assessing revenues as a ratio relative to the number of labor hours necessary to conduct a treatment provides a different picture of economic feasibility. Whether a silvicultural approach is more expensive to implement is a critical question. When we control for differences in operability between sites, SCE had a revenue to labor ratio that was 81% of the average for conventional treatments (figure 4). From this standpoint SCE may result in a small increase in labor costs relative to conventional treatments.

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 and structural complexity enhancement (SCE) systems tested maintain high levels of post-harvest structure and canopy cover. These are indicative of lower intensity, minimal impact forestry practices (Franklin et al. 2002, McEvoy 2004). However, SCE maintains, enhances, or accelerates develop of CWD, canopy layering, overstory biomass, large tree recruitment, and other structural attributes to a greater degree. In addition, SCE results in a rotated sigmoid diameter distribution that appears sustainable at least over 50 years, and consequently reallocates growing space and aboveground structure into larger size classes. This contributes to enhanced large tree structure, foliage biomass, and associated canopy complexity.

Both SCE and conventional uneven-aged treatments will result in accelerated tree growth rates according to model projections. Since the conventional treatments had significantly lower residual basal areas, this result is consistent with previous research on growth responses to stocking density in northern hardwoods (Leak et al. 1987). However, 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 and biomass are also higher after 50 years of development under SCE due to greater post-harvest structural retention. However, none of treatments are likely to develop basal areas or aboveground biomass exceeding levels that would have accumulated without treatment. Passive restoration may ultimately develop higher levels of these characteristics. However, that conclusion does not account for the accelerated rates of large tree recruitment, reallocation of basal area, and associated structural complexity projected for SCE. Active restorative approaches thus offer advantages with respect to development of canopy complexity and large tree structure.

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. Most of the newly added CWD is un-decayed. It is likely than decay class distributions will shift over time towards well-decayed material. As time passes, this will render silviculturally enhanced CWD

TABLE 2. Potential applications of SCE as an approach for incorporating old-growth structure into managed forests.

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

increasingly available as habitat and as a nutrient source (Tyrrell and Crow 1994a).

SCE may have a variety of useful applications, ranging from old-growth restoration, to riparian management, to low-intensity timber management and wildlife habitat enhancement. However, the degree of implementation and the number of stand entries will vary by application (Table 2). Management application will also depend greatly on economic feasibility under a variety of site quality, product, and market conditions (Niese and Strong 1992). The relatively low returns for SCE suggest that its feasibility is highly sensitive to site quality and market conditions. Where these are poor, SCE will at best cover expenses and at worst may result in a deficit. These scenarios might be acceptable in a limited number of settings, for instance where restoration funds are available for nature preserve management, or where access roads, landings, and skid trails are already paid for.

Where a positive profit margin is a required, SCE would be marketable where site quality (e.g. volume) is high and market conditions (e.g. lumber prices, fuel costs, and interest rates) are favorable. Under these conditions SCE offers an alternative that provides revenue from low-intensity harvest while also meeting ecological management objectives. Conventional uneven-aged approaches are also clearly sensitive to site quality and market conditions, and can result in deficits where these are poor. Conventional approaches are more robust economically in comparison to SCE only because harvest volumes are moderately higher on a per unit area basis, resulting in economies of scale. Both and SCE and conventional approaches would likely manifest economies of scale as treatment area increases due to lower cost to revenue ratios. Thus, SCE may be more feasible at larger scales of 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 of these or provide them to a more limited extent. 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 entries. The results show that SCE's 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 alternatives for retaining high levels of post-harvest structure and for promoting accelerated stand development.

ACKNOWLEDGEMENTS

This research was supported by grants from the USDA CSREES National Research Initiative, the Vermont Monitoring Cooperative, the Northeastern States Research Cooperative, and the USDA McIntire-Stennis Forest Research Program.

LITERATURE CITED

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.

Bush, R.R. 1995. Northeastern TWIGS variant of the Forest Vegetation Simulator. Forest Management Service Center. Available online at http:/ftp.fs.fed.us/pub/fmsc/fvs/doc/overviews/nevar.txt

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

Dahir, S.E. and C.G. Lorimer. 1996. Variation in canopy gap formation among developmental stages of northern hardwood stands. Canadian Journal of Forest Research 26:1875-1892.

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 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.

Keddy, P.A. and C.G. Drummond. 1996. Ecological properties for the evaluation, management, and restoration of temperate deciduous forest ecosystems. Ecological Applications 6:748-762.

Keeton, W.S. 2005. Managing for old-growth structure in northern hardwood forests. Pages 107-117 *in:* C.E. Peterson and D.A. Maguire (eds.). Balancing ecosystem values: innovative experiments for sustainable forestry. General Technical Report PNW-GTR-635. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 389 pp.

Keeton, W.S., C.E. Kraft, D.R. Warren, and A.A. Millward. 2005. Effects of old-growth riparian forests on Adirondack stream systems. Pages 39-43 in: K.P. Bennet (tech. ed.). Moving toward sustainable forestry: lessons from old-growth forests. Proceedings of the 6th eastern old-growth conference, Moultonborough, NH. University of New Hampshire Cooperative Extension Natural Resource Network Report.

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. 1987. Silvicultural guide for northern hardwood types in the Northeast (revised). USDA Forest Service Research Paper NE-603. 36 pp.

Lorimer, C.G. 2001. Historical and ecological roles of disturbance in eastern North American forests: 9,000 years of change. Wildlife Society Bulletin 29:425-439.

Lorimer, C.G. and A.S. White. 2003. Scale and frequency of natural disturbances in the northeastern U.S., implications fore early-successional forest habitats and regional age distributions. Forest Ecology and Management 185: 41-64.

McEvoy, T.J. 2004. Positive Impact Forestry. Island Press, Washington, D.C. 268 pp.

McGaughey, R.J. 1997. Visualizing forest stand dynamics using the stand visualization system. American Society of Photogrammetry and Remote Sensing 4:248-257.

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.

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.

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.

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.

Twery, M.J., P.D. Knopp, S.A. Thomasma, H. M. Rauscher, D.E. Nute, W.D. Potter, F. Maier, J. Wang, M. Dass, H. Uchiyama, A. Glende, and R.E. Hoffman. 2005. NED-2: A decision support system for integrated forest ecosystem management. Computers and Electronics in Agriculture 49: 24-43.

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.

Ziegler, S.S. 2000. A comparison of structural characteristics between old-growth and post-fire second-growth hemlock-hardwood in Adirondack Park, New York, U.S.A.. Global Ecology and Biogeography 9:373-389.