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TOWARD UNDERSTANDING THE ECONOMIC AND ECOLOGICAL OUTCOMES OF SELECTION SILVICULTURE ON A NORTHERN HARDWOOD FOREST

BY

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THESIS

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Masters of Science
in
Natural Resources: Forestry

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ABSTRACT

TOWARD UNDERSTANDING THE ECONOMIC AND ECOLOGICAL OUTCOMES OF SELECTION SILVICULTURE ON A NORTHERN HARDWOOD FOREST

by

Katherine Ann Sinacore

University of New Hampshire, September 2013

Single-tree selection (STS) and small-group selection (SGS) silviculture are widely used in the northeastern United States, but questions remain regarding the economic and ecological outcomes of these systems. To assess harvest treatment effects on northern hardwood forests, we examined an unmanaged stand (UNM) and STS and SGS managed stands within the Bartlett Experimental Forest of New Hampshire. For an economic perspective, grade and standing tree values were our metrics to evaluate changes in timber quality. After 60 years of management, the percentage of higher graded trees increased slightly for both the SGS and STS managed stands. However, current data suggests no statistically significant differences in the standing tree value among the UNM, STS, and SGS. For an ecological perspective, density and volume of downed woody debris (DWD) was used for assessing structural heterogeneity. SGS and UNM had the greatest volume and density of DWD.

INTRODUCTION

High quality timber production is a common forest management objective in northern hardwood forests of New England (Sendak et al., 2000). Uneven-aged management has frequently been used in this region to create structurally diverse forests while meeting timber production goals. Single-tree selection (STS) and small-group selection (SGS), two uneven-age treatments, have the potential to promote high-quality timber growth (Kelty et al., 2003), a common forest landowner objective.

Early research on STS and SGS silviculture focused on their ability to control species composition. These studies found that STS favors regeneration of shade tolerant species while SGS enhances regeneration success of mid- to intolerant species. More recent efforts have switched focus to evaluating the economic differences between management regimes. Such studies are becoming increasingly relevant as landowners want to maximize revenue during a harvest and, at the same time, improve the quality of the remaining trees. In fact, according to state surveys, the second most popular reason for New Hampshire landowners to harvest is to improve the quality of future trees (Appendix A). Although improvement harvests are among landowner objectives, studies evaluating the effectiveness of silvicultural prescriptions to improve timber quality and value find conflicting results. Whereas one study found silvicultural prescriptions have positive effects on timber quality (Trimble Jr, 1973), another suggests no effect (MacDonald and Hubert, 2002). These diverse conclusions suggest further research is needed. Results can often vary by region, forest type, and prescription type, making generalizations about silvicultural prescriptions problematic. .

Further difficulties lie in separating treatment effects from timber marking effects associated changes in tree grow and species composition (Webster and Lorimer, 2003). Marking effects stem from targeting trees for removal during a harvest. For example, in addition to removing high quality trees, poor quality trees are often removed as well to create space for new and existing tree growth. This marking process improves the quality of the forest and biases our conclusions about timber quality improvements. Fortunately, some of the issues associated with marking bias, tree growth, and species composition changes can be addressed by including an unmanaged treatment, which we propose in our study design.

In addition to studies focusing on the economic forestry perspective, forest management paradigms have expanded to include more ecological goals over the past two decades. Understanding the effects of silvicultural prescriptions on forest structural diversity is a valuable, but missing component of research in New Hampshire, although preserving forest structural diversity is a top priority among New Hampshire landowners (Appendix A). There are many indicators of forest diversity, but downed woody debris (DWD) serves as one key indicator. DWD not only functions as wildlife habitat, but also affects soil processes, soil fertility, and hydrology (McCarthy and Bailey, 1994), making it an effective metric for studying the ecological aspects of forest management. Early research has suggested that forest management practices often reduce DWD density, and volume, and affect distribution of DWD across the landscape (Fraver et al., 2002a), but these results are largely unconfirmed in our study area. To add to the growing body of knowledge and address landowner concerns, we propose to quantify the effects of STS and SGS systems on DWD and compare these findings to an unmanaged site.

SGS and STS are common forest management techniques in New England, yet information about the differences between ecological and economic outcomes of the two techniques is elusive. The objective of our research is to give forest managers and forestland owners scientific knowledge and increased confidence that their actions will supply desired products and critical ecological services specifically related to SGS and STS systems in a northern hardwood forest.

Report Organization

This report consists of three chapters comparing the economic and ecological effects of single-tree selection (STS) and small-group selection (SGS) silviculture to an unmanaged (UNM) control. The first two were written as manuscripts intended for submission to appropriate journals; therefore, they are largely independent and stand on their own. A conclusion at the end of the report discusses the combined results of both sections and explores possible management implications.

Chapter 2 covers the economic perspective of forest management. We address timber quality changes by comparing our 2012 field data to a 1952 study at the Bartlett Experimental Forest in Bartlett, New Hampshire. Chapter 2 also compares timber quality of an unmanaged control to our STS and SGS sites. We use tree grades and standing tree values as a proxy for evaluating timber quality.

Chapter 3 discusses the ecological side of forest management. Here, we address the effects of selection silviculture on volume, density, decay class, and diameter class of downed woody debris.

The concluding third chapter summarizes the results of the previous two chapters, discussing the economic and ecological outcomes of selection silviculture. We describe the limitations of our data and analyses, as well as potential management recommendations. Finally, we suggest areas that could benefit from additional research, with the goal of determining the long-term outcomes of selection silviculture in New Hampshire forests.

CHAPTER II

TIMBER QUALITY CHANGES IN A NORTHERN HARDWOOD FOREST AFTER 60 YEARS OF SELECTION SILVICULTURE

Abstract

Single-tree selection (STS) and small-group selection (SGS) silviculture are widely used in the northeastern United States, but questions remain regarding differences in the long-term economic outcomes between the two systems. To assess silvicultural prescription effects on the northern hardwood forests, we analyzed tree quality differences between STS and SGS treated stands within the Bartlett Experimental Forest of New Hampshire. To assess the economic outcomes between the systems, we evaluated the changes in timber quality by comparing mean tree grades over 60 years. To support these data, we used standing tree value on a sample of our current data to understand how these tree grades scale to market prices. Our data shows that, over time, highly valued tree grades increased in both harvest treatments slightly. Despite these tree grade improvements, no significant difference between standing tree value in the SGS, STS, and UNM sites were found.

Introduction

The northern hardwood forests, or beech-birch-maple forest type, spans across northern New England, west toward Wisconsin, and north toward southeastern Canada. The northern hardwood forest is the most common forest type found in New Hampshire (Brooks, 2003) a state that is 84 percent forested (NEFA, 2011). The northern hardwood forest is one of the most productive forest types in New Hampshire. Despite the pervasiveness and productivity of these forests, hardwood timber production has decreased over the past decades in the state.

Private landowners comprise over 70 percent of the ownerships, a trend that is typical in the eastern part of the United States (Mondal et al., 2013). Although private landowner objectives are diverse, a common reason for owning land in New Hampshire is to have access to the beauty or scenery it provides (Miles et al., 2001) (Appendix A). Another common reason, albeit dissimilar, is to own land for timber production. In fact, in addition to harvesting, landowner objectives include harvesting to improve the quality of future trees. Although these seem like competing objectives, there are forest management systems that can provide both the aesthetics and financial return landowners are seeking.

In response to strong public sentiment against wasteful timber harvesting, European forestry concepts were incorporated into North America in the early 1900s. Emerging concepts of uneven-age forestry were brought to the forefront of forest management at this time. The most popular uneven-age management options are single-tree selection (STS) and small-group selection (SGS) (O'Hara, 2002). Both these systems are capable of meeting the aesthetic and financial landowner objectives, although conclusive evidence is lacking.

STS targets individual trees for removal and promotes shade tolerant regeneration (Poulson and Platt, 1989). Previous studies show STS favors shade tolerant sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), and eastern hemlock (*Tsuga canadensis*) which, except for sugar maple, typically have lower commercial value than other northern hardwoods and softwoods (Leak, 2005; Legault et al., 2007). Conversely, SGS promotes regeneration of shade mid- to intolerant species that have higher commercial value through removal of groups of trees, creating openings larger than those in STS. Higher value, less shade tolerant species include eastern white pine (*Pinus strobus*), northern red oak (*Quercus rubra*), and paper birch (*Betula papyrifera*) (Leak and Filip, 1975)

In addition to owning forestland for timber harvesting, another important landowner objective in New Hampshire is to improve the quality of trees through harvesting. Little research has sought to understand the impacts of these systems on timber quality over time. If differences between systems exist, this information could directly inform future management decisions and help landowners decide, based on their objectives, the proper treatment for their forest. Studies evaluating the economic outcomes of forest management are becoming increasingly important with the downturn of the national economy and forest product markets putting pressure on forestland owners to choose management designs that successfully meet landowner goals.

For our study, we chose to use tree grades and standing tree value as our metrics to evaluate timber quality. In general, timber quality is based on the species, form, and number of defect free sides (Houllier et al., 1995). Quality of standing timber is differentiated by tree grades. One tree grade system for northern hardwoods developed by the US Forest Service gives details on the minimum requirements for a tree to meet grade classes (Hanks et al., 1980). A second guide to hardwood log grading describes the basic principles and gives detailed practical applications for grading in the field (Rast et al., 1973). Accurate grading is important because over an entire stand, slight differences in tree grades can equate to large differences in standing tree value (Rast et al., 1973).

Thus far, studies examining treatment effects on timber quality have had conflicting results, a consequence of uncontrollable environmental factors that act on the forest, independent of harvest treatment. Factors including stocking density, site quality, wind, slope, snow, and ice, can affect tree quality. For example, MacDonald et al. (2004) found high initial stocking densities create competition that reduces juvenile core and branching to a minimum in the tree bole, creating a greater portion of clear wood that allows a tree to be graded higher. Though high stocking densities can benefit tree quality, other factors can negatively affect tree quality. Poor site quality, wind, slope, snow, and ice not only affect timber quality negatively, but their effects can be exacerbated by opening the canopy through harvesting (MacDonald and Hubert, 2002). Canopy openings make trees more susceptible to these factors and result in trees with sweep, reducing the timber quality. These environmental factors in addition to variable stocking densities may have affected the outcomes of previous studies examining treatment effects on timber quality.

Overall, the effects of management on timber quality are understudied. Long term data are necessary in the Northeast where management typically adopts STS and SGS regimes that slowly alter the forest structure and species composition over many decades and whose effects might not be visible immediately. The objectives of our study are to assess harvest treatment effects on timber quality, specifically:

(1) To determine if there are long term differences in timber quality between SGS and STS by comparing tree grade changes over 60 years.

(2) To determine if there are any differences in standing tree value between SGS, STS, and an unmanaged control.

Methods

Site Selection & Description

Study sites are located in the Bartlett Experimental Forest in the White Mountain National Forest, Bartlett, New Hampshire (Figure 1) and include a single-tree selection (STS), small-group selection (SGS), and unmanaged (UNM) site (Leak and Sendak, 2002; Sendak et al., 2000)

Prior to harvesting a mix of American beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), and paper birch (*Betula payrifera*) dominated all three study sites. After sixty years of harvesting, American beech and eastern hemlock (*Tsuga canadensis*), dominate the all three sites while paper birch, sugar maple (*Acer saccharum*), white ash (*Fraxinus americana*), and yellow birch are now found in lesser quantities. In 2012, the most notable differences between the three sites is that striped maple (*Acer pensylvanicum*), bigtooth aspen (*Populus grandidentata*), and gray birch (*Betula populifolia*) are present in the SGS and UNM areas, but missing from the STS study area. The three harvest treatments are located between 355 meters (1100 feet) and 426 meters (1400 feet) in elevation and located on well drained glacial till soils (Filip, 1978; Leak and Filip, 1977).

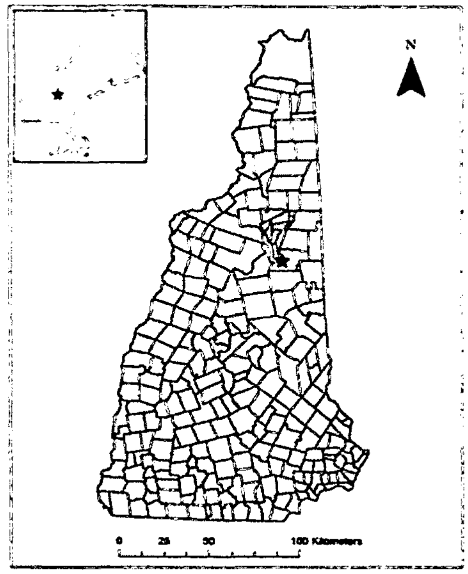

Figure 1. Location of the Bartlett Experimental Forest in New Hampshire and the northeastern United States (inset).

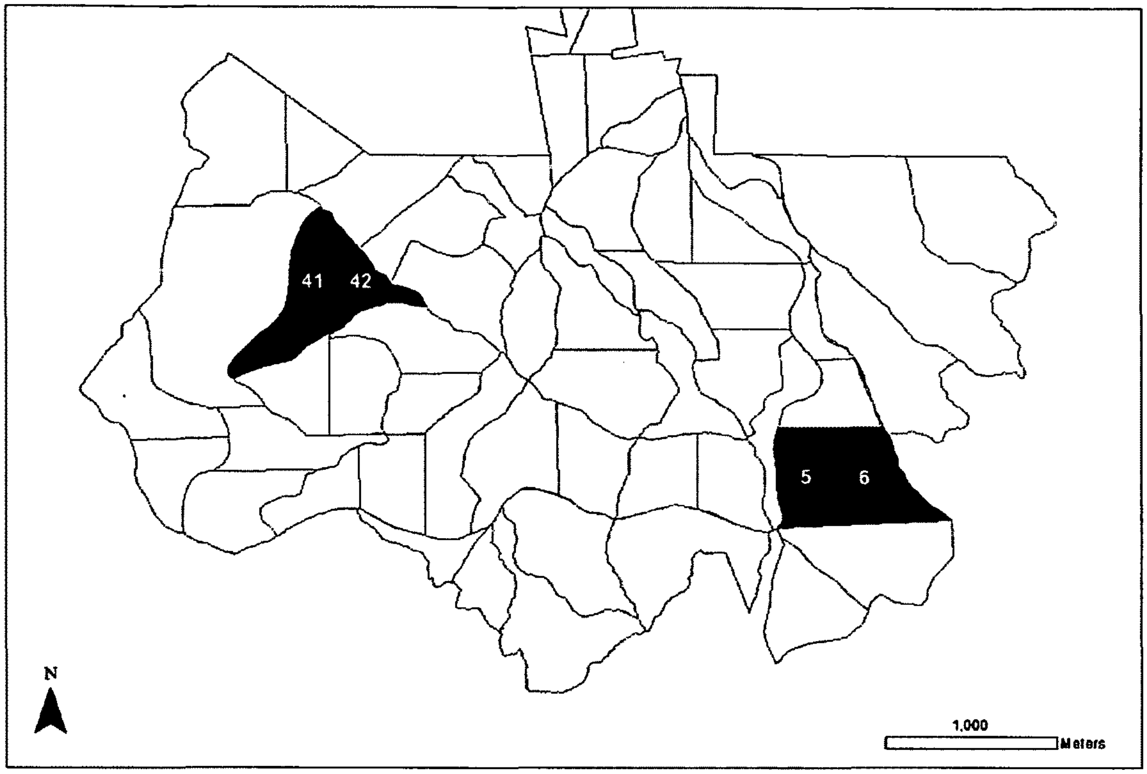

Figure 2. Location of study sites within the Bartlett Experimental Forest in Bartlett, NH. Compartments 5 & 6 treated by small-group selection, compartment 42 treated by single-tree selection, and compartment 41 is unmanaged.

Sites were selected for many reasons, but the most important were that these sites (1) represent typical northern hardwoods forests in New England dominated by shade tolerant species, (2) have previous, well-documented inventories from 1952 (with the exception of the unmanaged site), allowing for a unique 60 year comparison, and (3) have similar environmental characteristics and harvest timing histories (Table 1). We choose to have more sample plots in the SGS treatment than the STS and UNM because the area of the site is larger and the variability within the SGS is greater than the STS or the UNM treatments.

Table 1. Number of plots, compartment numbers, area, and elevation of three study sites in the Bartlett Experimental Forest, Bartlett, NH.

Treatment	No. Plots 2012	Compartment	Area (ha)	[d]Elevation (m)
[a]SGS	59	5 & 6	46.1	426.7
[b]STS	14	42	14.2	375.8
[c]UNM	31	41	27.5	400

[a]SGS = small-group selection; [b]STS = single-tree selection; [c]UNM = unmanaged; [d]Leak and Sendak (2002).

Data Collection

Data were collected during July and August, 2012. Plot locations were found using a handheld GPS and were generally accurate within 5 meters (~15 feet). A 20-basal area factor prism (20ft^2/acre; 4.59m^2/ha; referred to as 20-BAF below) was used to select sample trees at every sample point. Species was noted for all sample trees. Diameter at breast height (dbh) was measured to the nearest 0.254 cm (0.1 inch) using a research grade diameter tape. Sawlog height and pulpwood height of each bole was measured to the nearest half log (8 ft.; 2.67m) using a Biltmore stick. We chose to use half log measurements, because this in the minimum length required for sawlog product use and is the metric used in the 1952 studies to which we compare our 2012 data. The first log for all trees was graded following the rules developed by Hanks et al., (1980) and revised by Leak and Sendak (2002). We also field inventory methods from Rast et al., (1973) to evaluate the defect deductions for each tree. The minimum requirements for a tree to be in grades 1, 2, or 3 are outlined below (Table 2). In the Hanks et al., (1980) hardwood grading scheme, grades 4, 5, and 6 are also included. These grades were omitted from our grade analyses because they are low quality trees not suitable for sawtimber and were not always reported in previous inventories.

Table 2. Hardwood tree grades for factor lumber from Hanks 1973; adapted by Leak and Sendak 2002. Left panel lists requirements for a log to meet tree grade standards.

Grade factor	Tree grade 1	Trade grade 2	Tree grade 3
Length of grading zone (feet)	Butt 16	Butt 16	Butt 16
Length of grading section (feet)	Best 12	Best 12	Best 12
Dbh, minimum (inches)	16[a]	13	10
Clear cuttings (on 3 best faces):[c]			
Length, minimum (feet)	9	9	9
Cull deduction, including crook and sweep but Excluding shake, maximum within grading section (%)	9	9	50

[a]In ash, dib (diameter inside bark) at top of grading section must be 12 inches and dbh must be 15 inches

[b]Grade 2 trees can be 10 inches ib (inside bark) at top of grading section if otherwise meeting surface requirements for small 1s.

[c]A clear cutting is a portion of a face free of defects, extending the width of the face. A face is one-fourth of the surface of the grading section divided lengthwise.

The management history, environmental characteristics, 1952 sampling design, and 2012 sampling design for the STS, SGS, and unmanaged (UNM) treatments are outlined below.

Single-Tree Selection

The 1952 inventory was a 100% tally for species composition and tree grades to gain a better understanding of the forest dynamics and treatment impacts. All sawtimber trees were tree graded for hardwoods in the 27.9cm (11.0in) dbh class and larger and softwoods in the 22.7cm (9in) dbh class and larger. The 2012 inventory has fourteen 20-BAF prism plots on 80 m by 80 m spacing. All trees were graded using the same dbh minimums as in the 1952 inventory. Tree grading rules (Rast et al., 1973) followed methods outlined in the 1952 study (Table 2).

The STS treatment site (14.2 ha) was harvested in 1952, 1975, and 1992. The stand, initially an unmanaged, northern hardwood old-growth stand, was harvested leaving a residual basal area of 17.2-19.5 m^2/ha (75-80 ft^2/ac) for all trees greater than 12.7 cm (5 in) in diameter after each of the three harvests (Leak and Sendak, 2002). The timber markings were heavily weighted toward removing poor quality American beech in an attempt to eradicate beech-bark disease that infested the area in the late 1940s (Filip, 1978). The volume marked in 1952 was 45% beech and 24% over-mature paper birch. Nearly all of the sawtimber volume was tree grade 3. In the later markings, 75% of the harvested sawtimber volume was beech. (Leak and Sendak, 2002).

Small-Group Selection

The 1952 inventory consisted of 112 20-BAF plots on 60 m by 60 m spacing. The 2012 inventory consisted of 59 20-BAF prism plots on 80 m by 80 m spacing. Plots fell across a range of age classes, including uncut sites, recent cuts, and old cuts during both inventories. For both inventories in the SGS compartment, the tree grading followed Hanks et al. (1980) and Rast et al., (1973) methods, identical to those followed in the STS compartment (Table 2)

The SGS treatment (46.1ha) was harvested in 1937, 1951, 1960, and 1992 and provides the longest continuous record of SGS operations on the BEF. In 1937, the SGS sites was primarily mature and over-mature northern hardwoods with a strong component of eastern hemlock and red spruce (*Picea rubens*), and was high-graded prior to 1937 for the better softwoods. The SGS harvests since that time have averaged 0.2 ha (0.5 ac) (Table 3) (Leak, 1999).

Table 3. Harvest dates, number of patches, total hectares, average size, and size range for the small-group selection stand in the Bartlett Experimental Forest, Bartlett, NH. Derived from Leak 2002.

Dates	No. of Patches	Total Hectares	Average Size (hectares)	Size Range (hectares)
1937-1940	33	6.3	0.2	0.04-0.2
1951	38	6.5	0.2	0.08-0.3
1960	11	3.3	0.3	0.08-0.8
1992-1994	16	5.2	0.4	0.1-0.9
All	98	21.3	0.3	0.4-0.9

Unmanaged

Unmanaged (UNM) treatment (27.5 ha) is used as our control. The 2012 inventory consisted of thirty-one 20-BAF prism plots on 80 m by 80 m spacing. All trees in plots were graded according to methods outlined above (Table 2). Although a previous inventory of the unmanaged site exists, the inventory was from 1996 and used as part of a larger study assessing the standing value of timber across the White Mountain National Forest and Green Mountain (LeDoux et al., 2001). It did not provide the tree grade data we needed to compare an unmanaged stand over 60 years. Therefore, the unmanaged stand is used as a reference to compare SGS and STS standing tree values for 2012 and is not used to compare tree grade changes over time.

Data Analysis

Inventories prior to 2012 were collected and summarized by US Forest Service personnel. All 2012 inventories were collected in the summer of 2012 and summarized using the statistical software JMP Pro 10. We compared the percent tree grades by volume (n = 231 trees) for the 1952 and 2012 studies in the STS and SGS treatments. Percent tree grade by volume was used as a measure to compare the 1952 and 2012 because different sampling intensities were used for each inventory and percent relativized the two intensities allowing for a stronger comparison. Only grades 1, 2, and 3 were chosen for analysis because lower grades (4, 5, 6) refer to pulpwood and cull while the first three grades have the greatest value. Additionally, lower tree grades were not always reported in previous inventories.

In addition to measuring changes in tree grade over time, we also compared calculated standing tree values for the STS, SGS, and UNM sites in 2012. Standing tree value captures the relative value differences between species that our tree grade alone cannot. For example, an American beech tree graded 1 is worth far less than a paper birch tree graded 1. Standing timber value captures these relative differences whereas tree grades would consider grade 1 American beech and paper birch trees to be equivalent.

To calculate standing tree value, we used a model developed by the Timber Buyers Network. The model uses regression equations based on Hanks et al., (1973) to calculate individual standing tree values based on species, diameter, tree grade, price of 4/4 1 common lumber (see Appendix B), and number of merchantable logs. We calculated the standing tree value for all hardwood trees in our three study areas.

We hypothesize that harvest treatment and other environmental factors have an effect on the tree grade and standing timber value of a sample plot. We created mixed effects models to assess the amount of influence harvest treatment, species, and diameter have on mean tree grades and created a standard least squares model to assess the amount of influence harvest treatment had on standing timber value. In the mixed effect model, harvest treatment was treated as the fixed effect. We treated tree grade as continuous to allow for greater statistical power and inclusion of random effects. The conceptual linear model for assessing tree grade is:

$$Y = \beta_0 + \beta_1 \cdot \chi_1 + \beta_2 \cdot \chi_2 + E + T + R$$

Where Y is either mean tree grade or mean standing timber value; T is the indicator variable for treatment type (SGS, STS, or UNM), χ_n are the independent variables: species and diameter; β_n is a set of coefficients that reflect how each independent variable affects our estimates of tree grade.

For our analyses of standing timber value, we used a standard least squares model. For the standard least squares model, the conceptual linear model is:

$$Y = \beta_0 + \beta_1 \cdot \chi_1 + \beta_2 \cdot \chi_2 + E$$

Where Y is the mean standing timber value, χ_n is the nominal factors or harvest treatments (STS, SGS, UNM); β_0 is the coefficient reflection how harvest treatment affects our estimates of each dependent variable; E is the error term which includes effects of unmeasured factors on standing timber value. Our nominal factors, or harvest treatments, were treated as categorical variables with three possible levels. These nominal factors are transformed into indicator variables for the design matrix. In JMP, the same indicator columns for each nominal level except the last level are constructed. When the last nominal level occurs, a one is subtracted from all the other columns of the factor.

While we could have averaged all plots within a treatment to use as our sample unit for this model, this would yield low statistical power as we did not have replicates. Therefore, we decided to treat each plot as a replicate, and to acknowledge the problems associated with pseudo-replication. While the regression treats each plot as if it were independent from all others, our plots are clustered within one of three treatments and violate this assumption. Species was also treated as a categorical variable with 12 levels. We define our null hypothesis, H_0, as no independent variable has an effect on timber quality.

$$H_0 : \beta_n = 0 \quad \text{for all } n$$

The alternative hypothesis is that treatments, diameter, and species have an effect on the timber quality.

In addition to our tree grade and standing tree calculations, species composition was analyzed. Although a lesser part of our research objective, species composition is a direct consequence of harvest treatment so it was included here to explain treatment differences. We used relative dominance and density as opposed to tree biomass to measure species composition because many of our trees fell outside of the diameter ranges used in the species-specific regression equations developed for northern hardwoods and softwoods biomass estimates (Jenkins et al., 2004). Some studies use biomass regardless, but they are of limited usefulness because the biomass regressions chosen often do not cover the entire range of diameter classes found within their study area. In fact, these regression equations can often overestimate tree biomass, especially for larger trees (Somogyi et al., 2007), which make up a considerable portion of our inventory. Instead, we chose to report both density and basal area because they are good indicators of future species success and, in tandem, can provide useful information about species composition. Both indicators were considered to avoid placing more emphasis toward either big trees (basal area) or small trees (density).

Results

Tree Grade Changes

In the SGS treatment, we found no significant differences ($p = 0.05$) in tree grade changes. However, there was an increase in the percent of trees graded 1 or 2 while there was a decrease in the percent of tree grade 3 over time (Figure 3). Similarly, in the STS treatment, although not significant ($p = 0.05$), the percent of trees graded 1 increased slightly but the percent of tree grade 2 declined over 60 years. However, the percent of grade 3 trees in the SGS treatment remained largely the same (Figure 4). Another way to consider these changes was to compare the actual percent differences from 1952 to 2012. These data show that SGS had greater positive changes than STS in trees graded 1 (Figure 5).

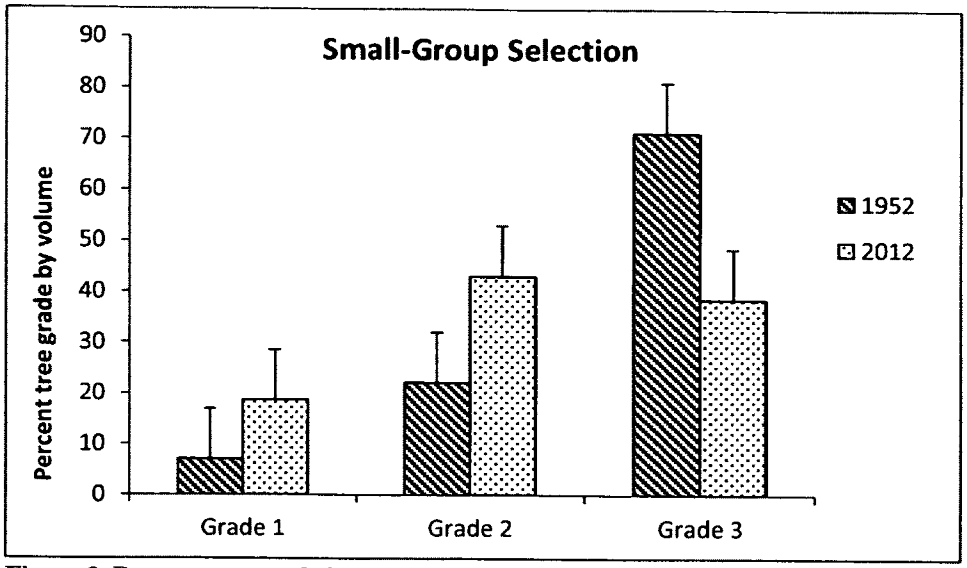

Figure 3. Percent tree grade by volume (n = 131 trees) in 1952 and 2012 within the small-group selection treatment. Error bars show ±1 SE. The change in Grade 3 is the only significant difference.

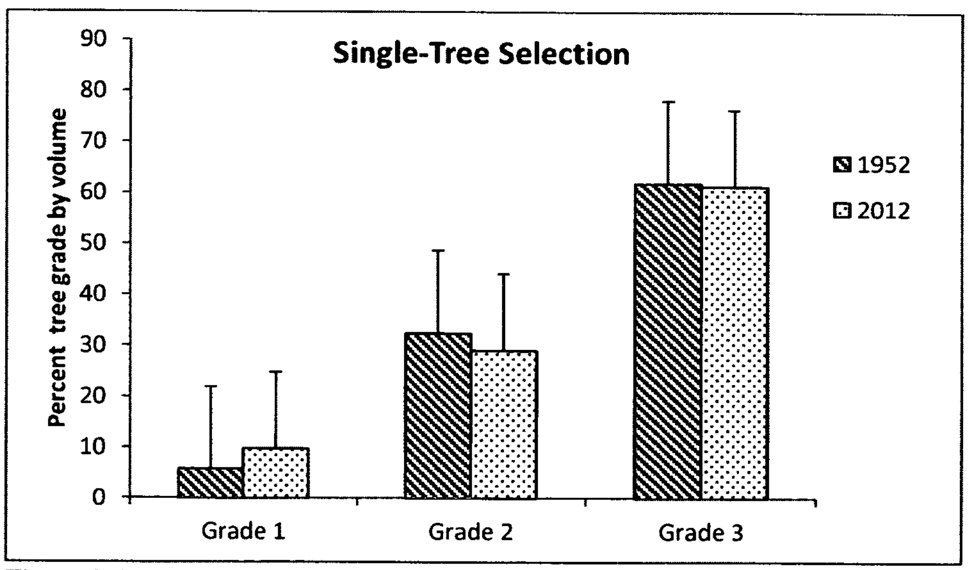

Figure 4. Percent tree grade by volume (n = 44 trees) in 1952 and 2012 within the single-tree selection treatment. Error bars show ±1SE. There are no significant differences between the changes from 1952 to 2012.

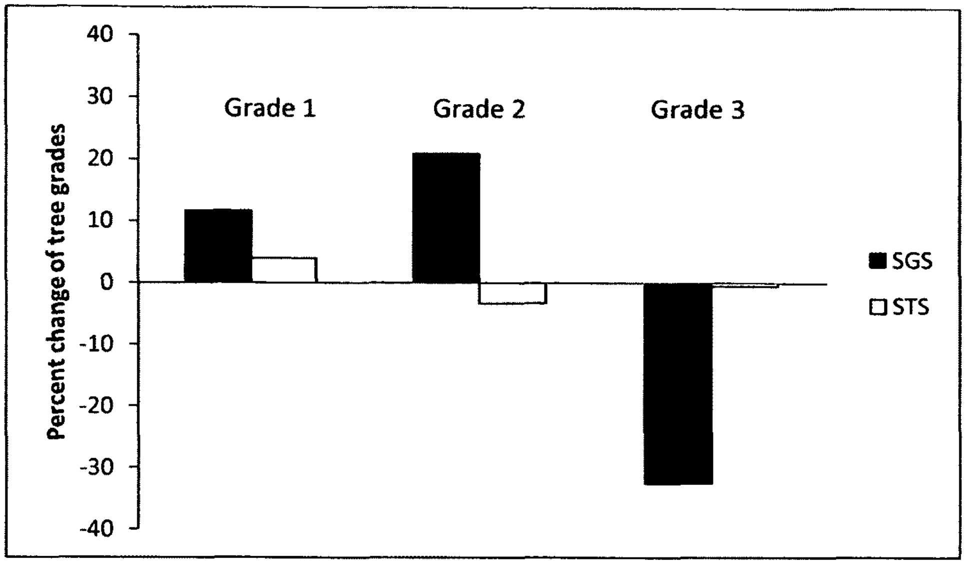

Figure 5. Percent tree grade changes from 1952 to 2012 in both the small-group selection (SGS) and single-tree selection (STS) stands in the Bartlett Experimental Forest, Bartlett, NH.

Tree Grade Model

We chose to examine our 2012 data using a mixed effect model predicting mean tree grade. Our model showed that SGS plots had slightly better tree grades, a difference that was significantly different from the unmanaged treatment (R^2 = 0.37, p = 0.049, n = 131, 79.97 d.f., Table 4, Figure 6) . Though the average tree grades in the STS were lower than the unmanaged site, these differences were not statistically significant (R^2 = 0.37, p = 0.2196, n = 44 61.72 d.f., Table 4, Figure 6). The same model showed that DBH did not have a significant role in average tree grade (R^2 = 0.37, p = 0.901, n = 231 d.f., 218.9, Table 4). Species was also included in our original mixed effects model. Of the most common species, American beech, big-tooth aspen, grey birch, eastern hemlock, paper birch, and red maple, and sugar maple had significant positive effects on the average tree grade (not shown) but the sample of some species was low so adequate conclusions could not be drawn from our sample. We removed species from our model, which increased the model's predictive power.

Table 4. Parameter estimates for the mixed effects model on tree grade averages. Positive parameter estimates indicate an increase in each fixed effect is correlated with an increase in the tree grade variable The standard error reflects the uncertainty in the parameter estimate. A low p < |t| value indicates a high likelihood that a given fixed effect has significant predictive power on tree grade; the degrees of freedom indicate our statistical power. Asterisks indicate statistical significance at the p < 0.05 level. Harvest treatment was treated categorically and the effects of small-group selection [SGS] and single-tree selection [STS] are reported as compared with the unmanaged treatment [UNM].

	Parameter estimate	Standard error	d.f.	t-ratio	p > |t|
Tree Grade					
Harvest Treatment [SGS]	-0.139336	0.069714	79.97	-2.00	0.0490*
Harvest Treatment [STS]	0.1002857	0.08087	61.72	1.24	0.2196
DBH (cm)	-0.006291	0.003696	218.9	-1.7	0.0901

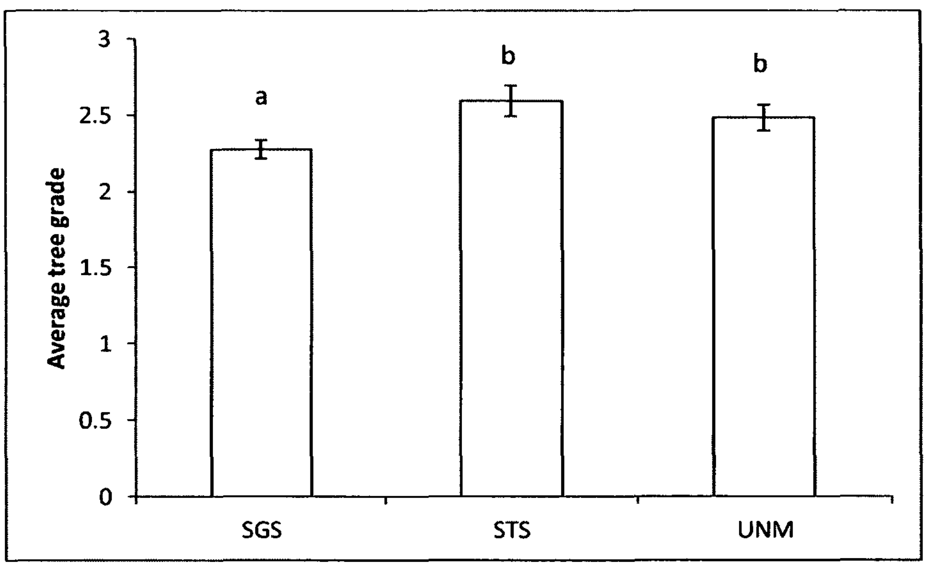

Figure 6. Tree grade compared among small-group selection (SGS), single-tree selection (STS) and unmanaged (UNM) study areas (n = 231 trees). Error bars represent the standard error of the mean. Harvest treatment effects of significant differences are noted by different letters. Data from experimentally harvested northern hardwood sites in the Bartlett Experimental Forest in Bartlett, NH. Short bars signify higher tree grades.

Standing Tree Value Model

Our model shows that neither SGS ($R^2 = 0.0208$ $p = 0.5586$, $n = 79$, Table 5) nor STS ($R^2 = 0.0208$, $p = 0.1059$, $n = 38$, Table 5) had a significant effect on standing tree value (Figure 7). The ability of this model to determine harvest treatment differences was not strong, given the low amount of replication.

Table 5. Parameter estimates for one fixed effect of the mixed effect model a tree value metric (n =166). Positive parameter estimates indicate an increase in the fixed effect is correlated with an increase in the tree value variable. The standard error reflects the uncertainty in the parameter estimate. A low p > |t| value indicates a high likelihood that a given fixed effect has significant predictive power on timber value. Asterisks indicate statistical significance at the p < 0.05 level. Harvest treatment was treated categorically the effects of small-group selection [SGS] and [STS] are reported as compared to an unmanaged [UNM] site.

	Parameter estimates	Standard error	t-ratio	p > |t|
Standing Tree Value				
Harvest Treatment [SGS]	12.80561	21.83475	0.59	0.5586
Harvest Treatment [STS]	-40.09685	24.61851	-1.63	0.1059

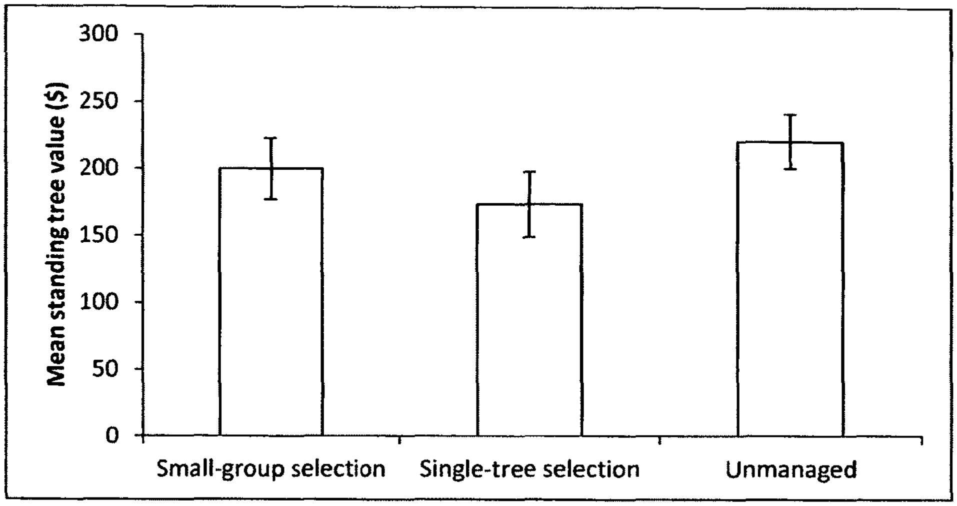

Figure 7. Average standing tree value among small-group selection (SGS), single-tree selection (STS) and unmanaged (UNM) study areas. Harvest treatments SGS and STS are compared to the unmanaged site (UNM). Error bars represent the standard error of the mean. Harvest treatment effects are not significant for differences in mean standing tree value.

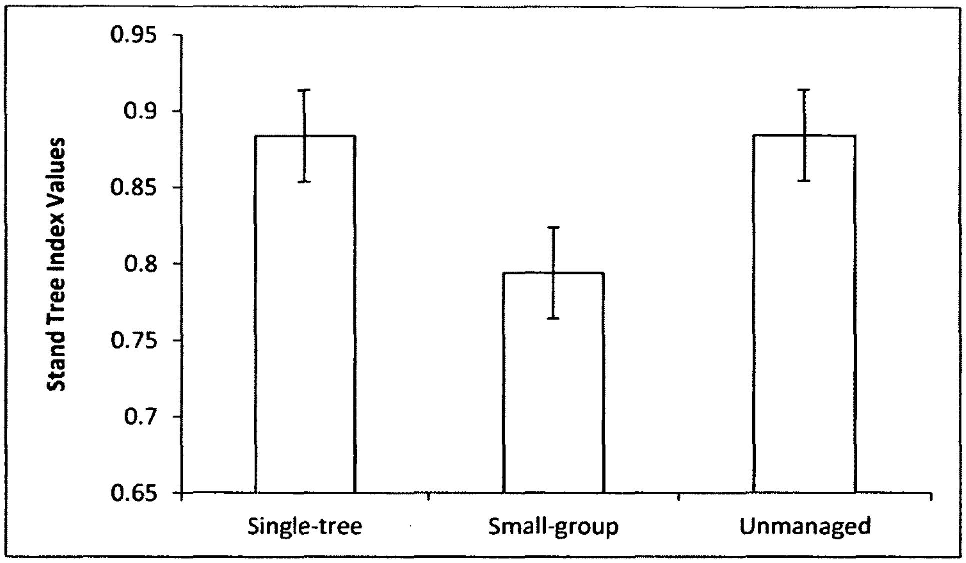

Figure 8. Standing tree index values among small-group (SGS), single-tree (STS), and unmanaged (UNM) study areas. Harvest treatments SGS and STS are compared to the UNM. Error bars represent the standard error of the mean. Harvest treatments SGS and STS are compared to the unmanaged site (UNM). Error bars represent the standard error of the mean. Harvest treatment effects are not significant for differences in mean standing tree value.

Species Composition

We examined species composition of our sites using relative density and relative dominance. We also chose to examine the relative densities and dominances of our stands using all sample trees (n = 690) and only using those trees falling greater than the minimum diameter requirements for our tree grade and value estimates (n = 321). American beech, eastern hemlock, sugar maple, red maple, and paper birch are pervasive throughout all three study areas when diameter is not considered (Figures 8 & 9). Where the treatments seem to differ is in the more shade intolerant species. Bigtooth aspen and gray birch are only found in the SGS treatment. Pin cherry, an early successional species, and striped maple, a gap specialist, were only found in the SGS and UNM treatments (Figures 8 & 9). A notable change we discovered is that red spruce, which was present during the 1952 inventory (Leak and Sendak, 2002), was missing from our inventories of all three study sites.

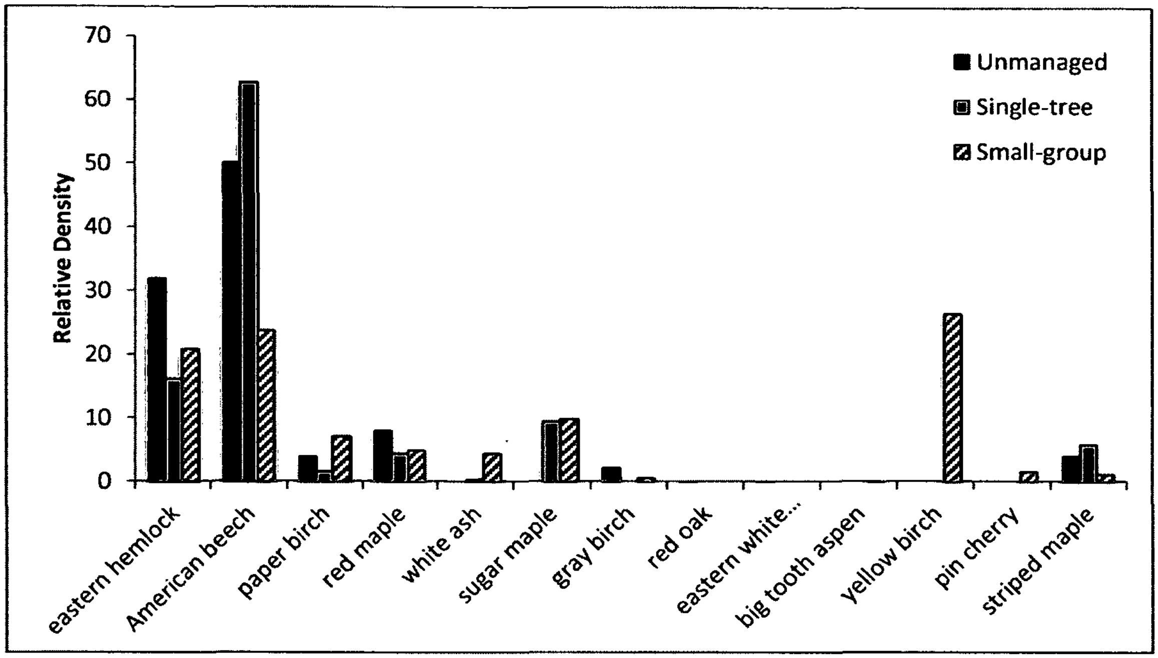

Figure 9. Relative density of all species (regardless of diameter) found in small-group selection (SGS), single-tree selection (STS), and unmanaged study (UNM) areas (n = 690 trees). These data are representative of the 2012 species composition in the Bartlett Experimental Forest, Bartlett, NH. The species to the right of the dashed line are absent from the single-tree selection study area.

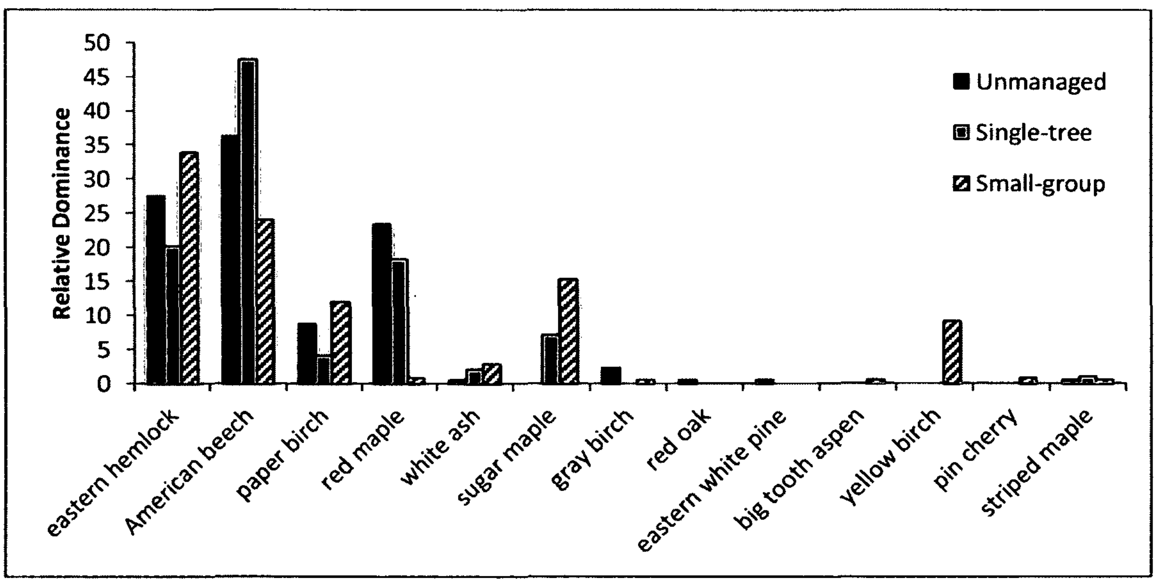

Figure 10. Relative dominance of all species (regardless of diameter) found in small-group selection (SGS), single-tree selection (STS), and unmanaged (UNM) study areas (n = 690 trees). These data are representative of the 2012 species composition in the Bartlett Experimental Forest, Bartlett, NH.

When we chose to look at the species composition of just the trees greater than the minimum diameter required for the tree grade and value analysis, the species composition changed in all three treatments. Most notably, gray birch and sugar maple relative densities and dominances declined (Figures 10 & 11).

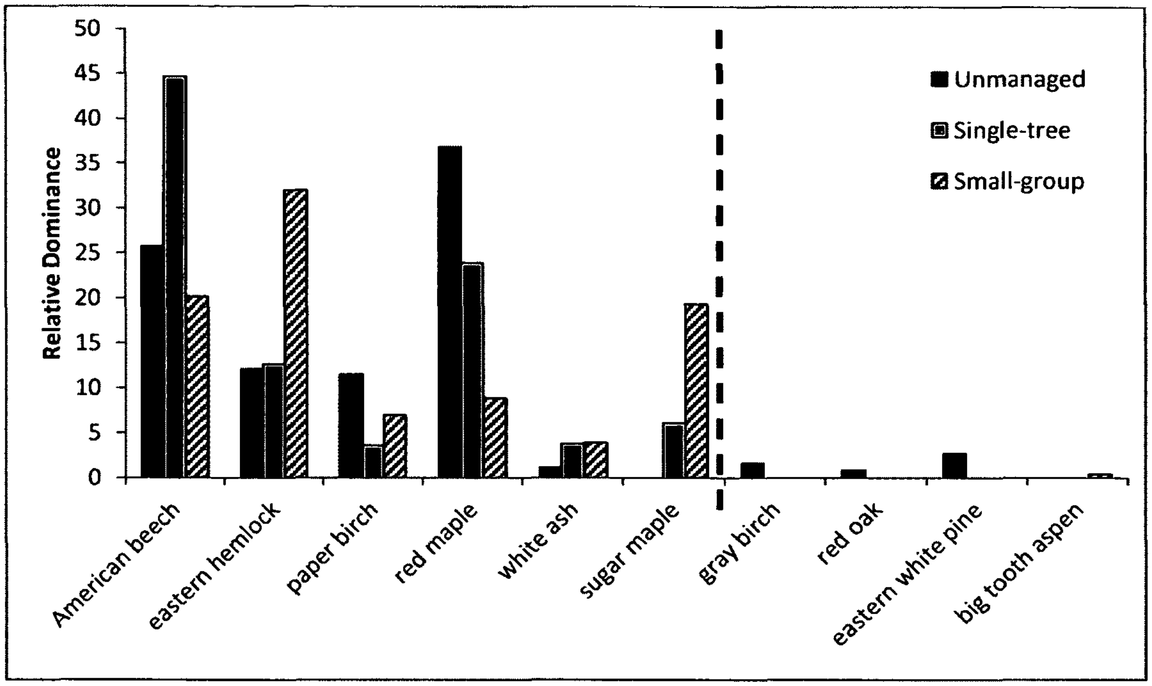

Figure 11. Relative dominance of all species (regardless of diameter) found in small-group selection (SGS), single-tree selection (STS), and unmanaged (UNM) study areas (n = 321 trees). These data are representative of the 2012 species composition in the Bartlett Experimental Forest, Bartlett, NH. The species to the right of the dashed line are absent from the single-tree selection study area.

Discussion

With economic pressures increasing, management decisions that provide landowners with revenue are becoming increasingly relevant. In the northeastern United States, where selection silviculture is common, understanding whether selection silviculture can sustainably supply revenue for landowners is a concern that needs to be addressed. Additionally, more landowners are seeking to use harvesting as a way to simultaneously improve the timber quality of their forest. Though both STS and SGS are thought to improve the timber quality, these findings do not hold true for all studies in our region.

Our data do not that that are differences in tree quality between the small-group and single-tree treated sites, however, the changes in quality showed strong trends. Notably, we found that the average tree grade was better in the SGS treatment than the STS treatment. This trend held true for our standing tree value comparison where SGS had a slightly greater average standing tree value than STS, but these differences were not statistically significant.

Environmental disturbances is one factor affecting tree growth and could explain the lower percent of high quality trees found in the STS treatment. One disturbance, beech bark disease, causes severe deformities in the bark and harms tree growth (Duchesne et al., 2005; McGee et al., 1999). Beech bark disease infected the site prior to the first harvest in 1952 and is still pervasive throughout the stand (Filip, 1978), despite intentional removal of infect trees throughout the harvest history. Since harvest treatment can alter species composition, and since STS promotes regeneration of American beech, improvements to tree quality in the STS stand might prove difficult due to these environmental forces.

Another explanation for why we see slight differences in timber quality between the two treatments might be related light availability. In the SGS, large openings (averaging 0.5 acres) were created allowing light to reach the forest floor. A high light environment and high competition, two factors found in gaps created by SGS, help keep tree boles straight. In contrast, STS creates small openings where the forest floor receives scattered light during a few hours of the day. Scattered light can promote crooked tree growth as trees grow at angles necessary to intercept light. Even mature trees near a recently removed tree form noticeable crooks when light availability suddenly changes (Crow et al., 2002; Gronewold et al., 2012).

The unmanaged compartment had the greatest proportion of low quality logs of all the treatments. Disturbance in the managed stand is characterized by single tree falls, which create small, scattered patches of light. Scattered light can promote crooked growth of trees as they try to grow toward light. This is similar to the disturbance simulated through STS, but this compartment had not been affected by beech bark disease as much as the STS treatment was, so that might be the reason the tree grades and standing timber values were slightly better than the STS site.

Although these reasons might explain our slight differences, we hypothesized that harvest treatment would have significant effects on timber quality (e.g., mean tree grade and standing tree value). We did not find any significant relationship between harvest treatment and timber quality. One explanation is that sixty years is not long enough to see treatment effects on tree value. In particular, trees must reach minimum diameter classes to be considered for grading. Many of our sample trees were just under the minimum diameter requirements necessary for grading, yet were defect free and had straight boles, making them good candidates for sawlogs in another few decades. We found this especially true in the SGS site where nearly 35% of trees were 10 inches diameter or less while less than 25% of trees in the STS were less than 10 inches diameter. It is possible that in another few decades, these trees will reach the diameter minimums and increase the percentage of higher grade trees. Interestingly, a study from sixteen years ago found slight positive effects of tree quality in the STS treatment when compared to the 1952 inventory (Leak and Sendak, 2002), yet we found no significant difference between 1952 and 2012 in the STS. These different results could be a function of random sampling where the Leak and Sendak (2002) sampled higher quality trees by chance or that the effects of STS are only starting to be noticeable after sixty years.

We predicted that SGS would outperform STS in both average tree grade and standing tree value. One of the reasons for this hypothesis is that SGS typically favors regeneration of higher value, mid- to intolerant species while the STS treatment typically favors shade tolerant species (e.g., American beech, eastern hemlock, sugar maple). The shade tolerant species – American beech, eastern hemlock, and sugar maple – typically have lower grades and have lower market values, with the exception of sugar maple. Additionally, these species tend to have crooked boles due to their light harvesting strategies, reducing their tree grade. The shade intolerant species associated with selection silviculture in New England typically grade higher because their boles are often straighter, with fewer defects. Additionally, these species also typically have greater market values than American beech and eastern hemlock.

One reason we did not see significant differences in standing tree value could be because the species composition between STS and SGS were not very different from one another. Both SGS and STS had shade tolerant species of lower value; these include American beech and eastern hemlock (Figure 9). Although the SGS selection treatment did have gray birch and big tooth aspen, which were absent from the single-tree selection treatment (Figure 9). Gray birch is a commercially valuable species, but very few of these were present in the SGS treatment. Big tooth aspen was also present, but only a few of these trees were found in the small-group treatment and are typically of low commercial value, regardless (Appendix B). Although this explanation explains why we did not see significant differences in standing tree value, we did see slight differences that can be attributable to many reasons.

A final reason for not finding any significant differences between timber quality could be a result of no replication. We were only able to examine three different sites for long-term changes. Often these datasets are rare and so our long-term comparison was limited to a small subsample of the northern hardwood forest.

One power of our study, however, is that our sites all have similar environmental factors, stocking density, and site qualities, enabling us to analyze the effects of treatment on tree grade and value more directly with less interference from uncontrollable environmental factors. Furthermore, our comparison to an unmanaged site shows that these treatments do improve timber quality relative to an unmanaged control treatment.

Conclusions

While the relationship between harvest treatment and timber quality is still somewhat unknown, our research suggests that treatment may have a small effect on tree grade and standing tree value. Whether this can be attributed to changing species composition, light levels, or other environmental factors, is still unknown. Sixty years of inventory in the BEF on the White Mountain National Forest is far from adequate on which to base tree quality conclusions. However, considering the lack of long-term field studies examining this question within New Hampshire, this research offers a perspective of northern hardwood stands managed under SGS and STS within a small sample of the region. Although neither conclusive nor applicable to all regions, these findings provide useful insights for managers in central New Hampshire.

We suggest that further research assess whether these differences span greater areas across New England and re-inventory these stands in another few decades to see if younger trees reach minimum diameter requirements to be graded. While this is not the final word on timber quality in SGS and STS treatments, these findings should be considered by forest managers as they choose prescription options that provide revenue and improve future tree quality. We also suggest these results be evaluated alongside other non-economic indicators of successful management, including parameters that assess overall forest health, wildlife benefits, and environmental services.

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CHAPTER III

STRUCTURAL HETEROGENEITY WITHIN MANAGED AND UNMANAGED NORTHERN HARDWOOD STANDS IN CENTRAL NEW HAMPSHIRE

Abstract

Downed woody debris (DWD) has long been valued for its role in providing ecological benefits, including wildlife habitat, nutrient cycling, and structural diversity. Despite its key roles, studies quantifying the abundance and type of DWD across managed and unmanaged forests are scarce throughout the northeastern United States, where percent cover is the metric most cited instead of volume and densities. Our study quantifies the amount and type of DWD in two selection silviculture treatments and an unmanaged forest in central New Hampshire. We found that the small-group selection (SGS) treatment most closely replicated the amount and type of DWD found in our unmanaged (UNM) site. Single-tree selection (STS), however, had significantly less DWD than the UNM site. We believe volumes and types of DWD should be an important consideration during the forest management planning process for its role in ecosystem services and wildlife habitat.

Introduction

The northern hardwood forest, which spans the northeastern United States, west toward Wisconsin, and north toward southeastern Canada, is one of the most productive forest types. In New Hampshire, where nearly 84 percent of the land is forested (NEFA, 2011), harvesting is occurring throughout the state. However, 70 percent of ownerships are private families (Mondal et al., 2013), where the landowner objectives are different from those of larger industrial or investment ownerships. For example, reasons for private ownerships span from scenic purposes to wildlife to small harvest operations.

Because of these ownership objectives selection silviculture is often prescribed in this region. Selection silviculture has the ability to keep the forest canopy intact, making the harvests less obvious than their even-aged counterparts that remove trees from large areas. Additionally, this type of harvesting has been shown to not adversely affect wildlife communities (Thompson et al., 2003). Emerging concepts of harvesting sustainably has surfaced in recent decades, but research assessing the sustainability or environmental impact of these systems is present (Bolton and D'Amato, 2011; Burrascano et al., 2013; Currie and Nadelhoffer, 2002) but has only touched the surface.

Long-term sustainability has often been assessed through determining harvest effects on wildlife. In fact, many studies have already assessed harvest effects on song bird (Doyon et al., 2005; Easton et al., 2002; Jobes et al., 2004; Kilgo et al., 1999) small mammal (Ford et al., 2000; Fuller et al., 2004; Klenner and Sullivan, 2003), and amphibian (Graeter, 2005; Harpole and Haas, 1999; Karraker and Welsh Jr, 2006) communities. Additionally, with the popularity of biomass for energy increasing, studies have looked at how harvesting might benefit this new fuel source (Keeton et al., 2011; Littlefield and Keeton, 2012). A common finding among all of these studies is that the amount of downed woody debris (DWD) is the key indicator for wildlife success. For our research, downed woody debris is defined by any log on the forest floor that is greater or equal to 5cm in diameter and is less than 45° from horizontal.

Interestingly, despite the necessity of DWD for all these species groups, estimates of DWD are scarce in the literature. In fact, percent cover is commonly cited when providing estimates of DWD instead of volumes or densities per hectare. Quantifying the amount and type of DWD throughout managed and unmanaged forest landscapes is a crucial, but missing part of research in the northern hardwood forests. DWD has implications for both the functioning of forested ecosystems, but is also a measure of forest sustainability, an important landowner objective in New Hampshire (Appendix A). Even more importantly, forest management can directly impact the amount of downed woody debris.

Historically, forest management has been known to reduce the amount of DWD throughout the forest, a concern for advocates of forest structural diversity. However, this bias might be unfounded. A few studies have already showed that different harvesting intensities are associated with different amounts of DWD debris (Fraver et al., 2002b; Stevenson et al., 2006), where some silvicultural prescriptions closely mimic the amount of DWD found in unmanaged stands. Furthermore, type or decay class of DWD is also shown to vary across different treatment and age classes (D'Amato et al., 2008; Sturtevant et al., 1997). Having large and heavily decayed DWD is important for wildlife purposes and nutrient cycling, respectively (Bowman et al., 2000; Laiho and Prescott, 2004).

For this very reason, we chose to study small-group selection (SGS) and single-tree selection (STS) silviculture as our two uneven-age study systems. SGS is a selection silviculture technique that removes small groups of trees while STS is a prescription that removes individual trees. We chose these two systems to study for many reasons. First, these systems are commonly used in the northeastern United States. Second, our study areas have been harvested with these treatments for over 60 years, allowing us to quantify the amount and type of DWD after long-term management. Third, selection silviculture is supposed to mimic natural disturbance; therefore, the amount and type of DWD might clearly mimic those in unmanaged forests. Fourth, these two systems are often chosen for their ability to provide timber revenue while also managing for structural diversity. We want to put these assumptions to the test. Finally, the effects of management, and in particular selection silviculture, on abundance and type of DWD are understudied in the northeastern United States. This type of information is crucial for landowners to make informed decisions backed by data. The objectives of our study are to quantify harvest treatment effects on the volume, density, and type (decay class) of downed woody debris, specifically:

(1) To determine if there are differences in DWD density (pieces ha^{-1}) and volume (m^3 ha^{-1}) among the SGS, STS, and unmanaged (UNM) harvest treatments.

(2) To determine if there are any differences in the distribution of decay classes among the SGS, STS, and UNM harvest treatments.

Methods

Site Selection & Description

Study sites are located in the Bartlett Experimental Forest in the White Mountain National Forest, Bartlett, New Hampshire (Figure 10) and include a single-tree selection (STS), small-group selection (SGS), and unmanaged (UNM) site (Figure 11). Sites were selected for many reasons, but the most important are that these sites (1) represent typical northern hardwoods forests in New England dominated by shade tolerant species, and (2) have similar environmental characteristics and harvest timing histories (Table 6). We chose to sample at a greater intensity in the SGS treatment compared to the STS or UNM treatments because the SGS treatment had a larger area and greater variability than the other two treatments.

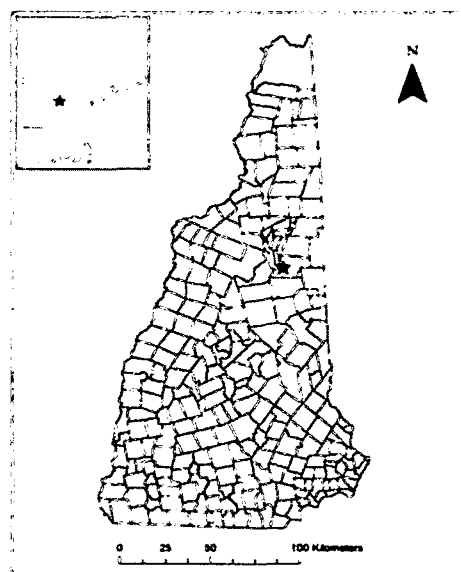

Figure 12. Location of the Bartlett Experimental Forest in New Hampshire and the northeastern United States (inset).

Prior to harvesting, a mix of American beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), and paper birch (*Betula payrifera*) dominated all three study sites

(Leak and Filip, 1975). After sixty years of harvesting, American beech is still present, but now eastern hemlock (*Tsuga canadensis*) and striped maple (*Acer pensylvanicum*) also dominate the sites while paper birch, sugar maple (*Acer saccharum*), white ash (*Fraxinus americana*), and yellow birch are now found in lesser quantities. The three harvest treatments are located between 355 meters (1100 feet) and 426 meters (1400 feet) in elevation and located on well drained glacial till soils (Filip, 1978; Leak and Filip, 1977).

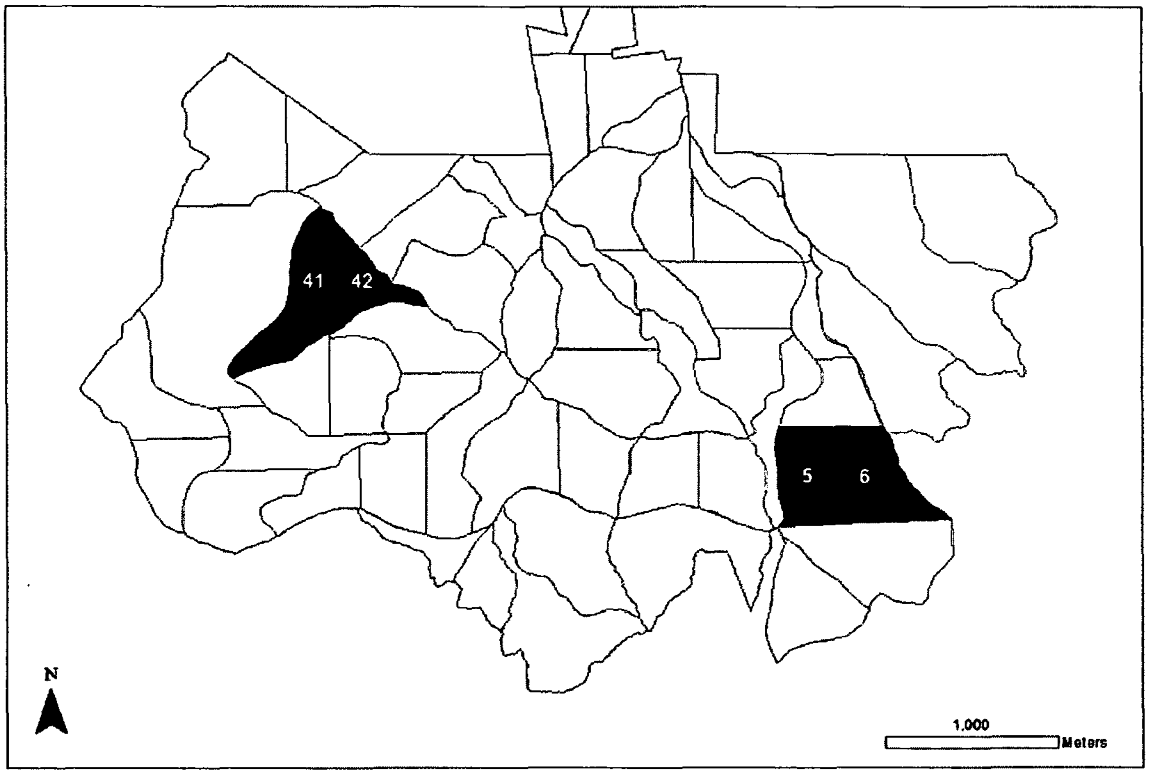

Figure 13. Location of study sites within the Bartlett Experimental Forest in Bartlett, NH. Compartments 5 & 6 treated by small-group selection, compartment 42 treated by single-tree selection, and compartment 41 is unmanaged.

Table 6. Number of plots, compartment numbers, area, and elevation of three study sites in the Bartlett Experimental Forest, Bartlett, NH.

Treatment	No. Plots 2012	Compartment	Area (ha)	[d]Elevation (m)
[a]SGS	59	5 & 6	46.1	426.7
[b]STS	14	42	14.2	375.8
[c]UNM	31	41	27.5	400

[a]SGS = small-group selection; [b]STS = single-tree selection; [c]UNM = unmanaged; [d]Leak and Sendak (2002).

Data Collection

Data were collected during July and August 2012. Plot locations were found using a handheld GPS and were generally accurate within 5 meters (~15 feet). For DWD density and volume sampling we used the line-intercept sampling (LIS) technique (Ringvall and Stahl, 1999; Van Wagner, 1982). We centered a line over the overstory plot centers. Forty meters of line (horizontal distance) were used per sample point – 20 meters (~66ft) were laid out in one direction and 20 meters in the opposite direction. Since fallen logs are unlikely to be randomly distributed or oriented (Bell et al., 1996), transect lines were laid out in a randomized bearing at each plot – ranging between 0° and 360°. For example, if our first bearing was 40°, we set up a line 20m on a bearing of 40°using hand compass. The second 20m line was set in the direction of 220°.

For each downed log intersecting the transect lines, we measured diameter where the log crossed the line for all logs greater or equal to 5cm diameter and measured the length of the log (Brown, 1974; Waddell, 2002). We measured the angle of the log to horizontal using a clinometer and noted the decay class (Woodall et al., 2008). Downed debris fell into one of five decay classes (Table 7). Decay classes were decided based on structural integrity, texture of rotten portions, color of wood, invading roots, and branch or twig integrity. A decay class of 1 denotes a downed log that recently fell while a decay class of 5 signifies a log that is highly decomposed.

Table 7. Decay class system for DWD derived for sampling in northern hardwood forests of the northeastern United states. (Woodall et al., 2008). Decay class is based on structural integrity, texture of rotten portions, color of wood, invading roots, and branch and twig presence.

Decay class	Structural integrity	Texture of rotten portions	Color of wood	Invading roots	Branches & twigs
1	Sound, freshly fallen, intact logs	Intact, no rot; conks of stem; decay absent	Original color	Absent	Branches are present, fine twigs still are attached and have tight bark
2	Sound	Mostly intact; soft (starting to decay) but cannot be pulled apart by hand	Original color	Absent	Branches are present, many fine twigs are absent with those remaining having peeling bark
3	Heartwood sound; piece supports its own weight	Hard, large pieces; sapwood can be pulled apart by hand or sapwood absent	Reddish-brown or original color	Sapwood only	Branch stubs will not pull out
4	Heartwood rotten; piece does not support its own weight, but maintains its shape	Soft, small block pieces; metal pin can be pushed into heartwood	Reddish- or light brown	Througho ut	Branch stubs pull out
5	None; pieces no longer maintains its shape; it is spread out on the ground	Soft; powdery when dry	Red-brown to dark brown	Througho ut	Branch stubs and pitch pockets have usually rotted down

In cases where our transect lines ran across the treatment boundary, we doubled back on the line to complete the required length; this means some logs were tallied twice. For example, if one 20 meter line hits a boundary at 14m, everything between 14m and 8m was tallied twice to complete the sampling distance (Ducey et al., 2004).

Although a lesser part of our overall study, we sampled species composition to gain a better sense of the stands diversity, another important measure of forest management sustainability. To sample for species composition, we sampled all trees with a 20-BAF prism for diameter and species on a systematic grid of 80m by 80m spacing. These were on the same plots used for our downed woody debris measurements.

The management history, environmental characteristics, and sampling design for the STS, SGS, and unmanaged (UNM) harvest treatments are outlined below.

Single-Tree Selection

The STS treatment site (14.2 ha) was harvested in 1952, 1975, and 1992. The stand, initially an unmanaged, northern hardwood old-growth stand, was harvested leaving a residual basal area of 17.2-19.5m^2/ha (75-80ft^2/ac) for all trees greater than 12.7cm (5in) in diameter after each of the three harvests (Leak and Sendak, 2002). The timber marking were heavily weighted toward removing poor quality American beech in an attempt to eradicate beech-bark disease that infested the area in the late 1940s (Filip, 1978). The volume marked in 1952 was 45% beech and 24% over-mature paper birch. In the later markings, 75% of the harvested sawtimber volume was beech (Leak and Sendak, 2002). For our DWD inventory, we had 14 plots on 80m by 80m spacing. All downed logs were sampled for abundance and type using methods outlined above.

Small-Group Selection

The 46.1ha (114ac), northern hardwood SGS compartment was harvested in 1937, 1951, 1960, and 1992 and provides the longest continuous record of SGS operations on the BEF (Table 3). In 1937, the compartments were primarily mature and over-mature northern hardwoods with a strong component of eastern hemlock and red spruce (*Picea rubens*), and was slightly high-graded prior to 1937 for better softwoods. In 2012, 59 plots on 80m by 80m spacing were sampled for DWD abundance and type.

Table 8. Harvest dates, number of patches, total hectares, average size, and size range for the small-group selection stand in the Bartlett Experimental Forest, Bartlett, NH. Derived from Leak 2002.

Dates	No. of Patches	Total Hectares	Average Size (hectares)	Size Range (hectares)
1937-1940	33	6.3	0.2	0.04-0.2
1951	38	6.5	0.2	0.08-0.3
1960	11	3.3	0.3	0.08-0.8
1992-1994	16	5.2	0.4	0.1-0.9
All	98	21.3	0.3	0.4-0.9

Unmanaged

The 27.5 ha (68 ac), northern hardwood, unmanaged (UNM) compartment has only been inventoried in 2012. The 2012 inventory consisted of 14 plots on 80m by 80m spacing. We sampled for DWD in 2012 following the same guidelines outlined previously. We chose to sample an unmanaged plot as a source from which to base the volume and densities of the STS and SGS harvest treatments.

Data Analysis

Inventories were collected in the summer of 2012 and summarized using the statistical software JMP Pro 10. We compared mean volume, mean density, and decay class distributions of DWD among the STS, SGS, and UNM harvest treatments. We used LIS which samples downed logs with probability proportional to their size. Since larger and longer logs have a greater chance of crossing the line, the probability of a log crossing a line is directly proportional to the length of the log as projected in the horizontal plane. This is also known as probability proportional to size, a similar technique to prism cruising which samples probability proportional to basal area, and each tree counts as a fixed amount of basal area per acre, or the basal area factor. In LIS, with probability proportional to length, each downed log counts as a fixed amount of linear length per acre, or the length factor (LF). The LF depends on the length of line run for each sample point. Each log that crosses the line counts as the LF of a log per unit area. Each log counts as the LF/l_H where l_H is the straight-line horizontal distance between ends of the log; this is also known as the expansion factor. The horizontal distance is calculated using the slope length of the log and the angle the log is from horizontal. To find out how much volume per hectare a log counts as, we multiplied the volume of each log by the expansion factor. To estimate logs per hectare at a point, we summed the expansion factors of the tallied logs. Since we had multiple points throughout all three treatments, we found logs per hectare by averaging the estimates from individual points

Estimates of fallen log length per unit area were converted to volume using the diameter of the log at the intersection point with the transect line and assuming a circular cross-section for all logs (Shiver and Borders, 1996). Density was determined using LIS conversion methods (Williams et al., 2005) and both abundance measures were corrected for slope (Stahl et al., 2002). Decay classes were determined and the distribution of decay classes was examined by harvest treatment. We also analyzed how volume of DWD varied by diameter size classes across treatments.

We hypothesize that harvest treatment has an effect on the mean downed woody debris volume and density. We created standard least squares models to assess the influence harvest treatment has volume and density of downed woody debris for our data. Our conceptual linear model is:

$$Y = \beta_0 + \beta_1 \cdot \chi_1 + \beta_2 \cdot \chi_2 + E$$

Where Y is mean volume, density, or decay class; χ_n represents the nominal factors or harvest treatments (STS, SGS, UNM); β_x are the coefficients reflecting how harvest treatment affects our estimates of each dependent variable; E is the error term which includes the effects of unmeasured factors on the volume or density variables. Our nominal factors, or harvest treatments, were treated as categorical variables with three possible levels. These nominal factors are transformed into indicator variables for the design matrix. In JMP, the same indicator columns for each nominal level except the last level are constructed. When the last nominal level occurs (in our analyses, that is the UNM treatment), a one is subtracted from all the other columns of the factor.

While we could have averaged all plots within a treatment to use as our sample unit for the model, this would yield low statistical power as we did not have replicates. Therefore, we decided to treat each plot as a replicate, and to acknowledge the problems associated with pseudo-replication. While the regression treats each plot as if it were independent from all others, our plots are clustered within one of three treatments and violate this assumption. We are aware of the problems associated with this, and consider the result of the regression only in the context of our study unit. We define the null hypothesis H_0 – that no independent variable affects the volume or density.

$$H_0 : \beta_n = 0 \text{ for all n}$$

The alternative hypothesis is that harvest treatment has an effect on the mean volume and mean density.

In addition to our analyses of DWD, species composition was analyzed. Although a lesser part of our research objective, species composition is an important consideration for diversity management. We used relative dominance and density as opposed to tree biomass to measure species composition because many of our trees fell outside of the diameter ranges used in the species-specific regression equations developed for northern hardwoods and softwoods biomass estimates (Jenkins et al., 2004). Some studies use biomass regardless, but they are of limited usefulness because the biomass regressions chosen often do not cover the entire range of diameter classes found within their study area. In fact, these regression equations can often overestimate tree biomass, especially for larger trees (Somogyi et al., 2007), which make up a considerable portion of our sample inventory. Instead, we chose to report both density and basal area because they are good indicators of future species success and, in tandem, can provide useful information about species composition. Both indicators were considered to avoid placing more emphasis toward either big trees (basal area) or small trees (density).

Results

Downed-Woody Debris Volume

We chose to use the mixed effects model platform in JMP Pro 10 to run a standard least squares model. Our model predicted mean volume of DWD by harvest treatment. Our model showed that SGS plots had greater volumes of DWD than our STS harvest treatment (Figure 12). Additionally, the SGS more closely resembled the UNM treatment ($R^2 = 0.055$, $p = 0.6691$, $n = 333$, Table 9. The STS had the least amount of DWD volume and was considerably less than the UNM site ($R^2 = 0.055$, $p = 0.0442$, $n = 46$, Table 9), a relationship that was statistically significant. Given the low amount of replication, the ability of this model to determine harvest treatment differences was not strong.

Table 9. Parameter estimates for linear model DWD volume by harvest treatment (n = 593 logs). Positive parameter estimates indicate an increase in each fixed effect is correlated with an increase in the in the DWD volume. The standard error reflects the uncertainty in the parameter estimate. A low p < |t| value indicates a high likelihood that a give fixed effect has significant predictive power on DWD volume. Asterisks indicate statistical significance at the p < 0.05 level. Harvest treatment was treated categorically and the effects of small-group selection [SGS] and single-tree selection [STS] are reported as compared with the unmanaged [UNM] treatment.

	Parameter estimate	Standard error	t-ratio	p > |t|
Downed Woody Debris Volume				
Treatment [SGS]	27.017376	63.01711	0.43	0.6691
Treatment [STS]	-187.6486	92.015424	-2.04	0.0442*

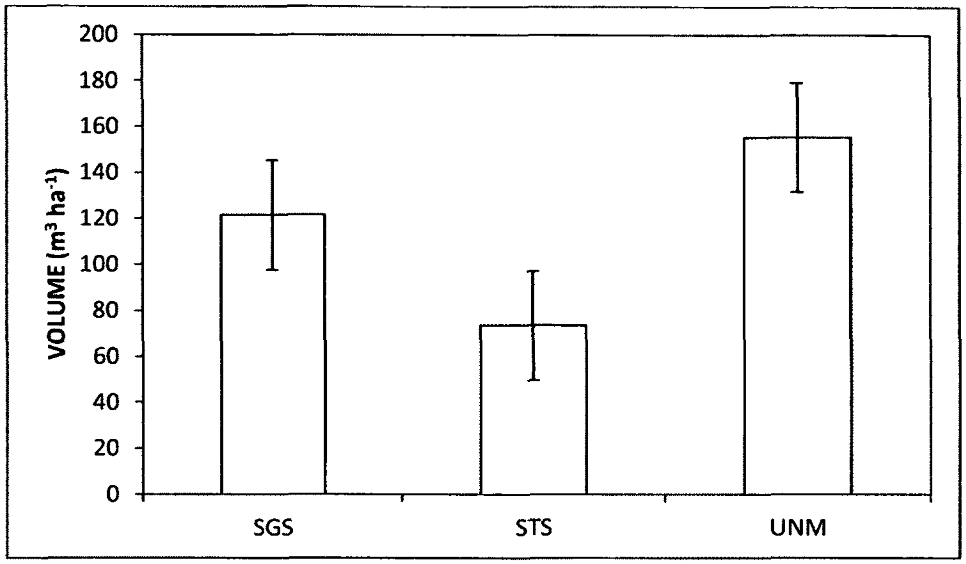

Figure 14. Mean volume of DWD compared among small-group selection (SGS), single-tree selection (STS) and unmanaged (UNM) study areas (n = 593 logs). Error bars represent the standard error of the mean. STS is significantly different from the UNM but SGS is not. Data from experimentally harvested northern hardwood sites in the Bartlett Experimental Forest in Bartlett, NH. Errors bars show ±1SE.

Downed-Woody Debris Density

We plotted harvest treatment against density of downed woody debris using a linear model in the mixed effect platform within JMP Pro 10, similar to our volume model (Figure 13). We found that the density of DWD in the STS was statistically different from the UNM treatment ($R^2 = 0.127$, $p = 0.0037$, $n = 46$, Table 10), but SGS was not statistically different from the UNM treatment ($R^2 = 0.127$, $p = 0.8247$, $n = 333$, Table 10). Given the low number of replication, the ability of this model to determine harvest treatment differences was not strong.

Table 10.Parameter estimates for linear model DWD density by harvest treatment (n = 593 logs). Positive parameter estimates indicate an increase in each fixed effect is correlated with an increase in the in the DWD density. The standard error reflects the uncertainty in the parameter estimate. A low p < |t| value indicates a high likelihood that a give fixed effect has significant predictive power on DWD density. Asterisks indicate statistical significance at the p < 0.05 level. Harvest treatment was treated categorically and the effects of small-group selection [SGS] and single-tree selection [STS] are reported as compared with the unmanaged [UNM] treatment.

	Parameter estimate	Standard error	t-ratio	p > |t|
Downed Woody Debris Density				
Treatment [SGS]	9.4222552	42.42976	0.22	0.8247
Treatment [STS]	-184.2408	61.95436	-2.97	0.0037*

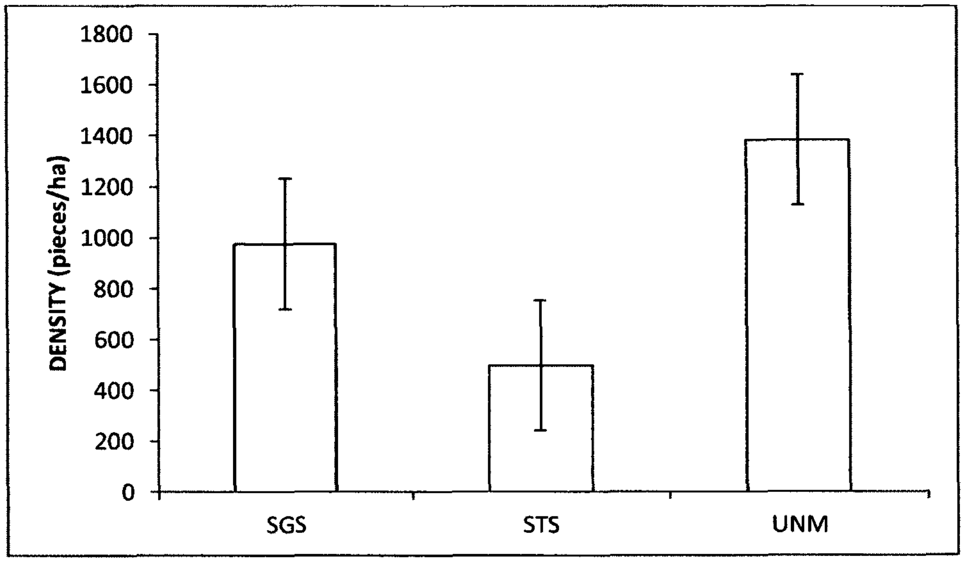

Figure 15.Mean density of DWD compared among small-group selection (SGS), single-tree selection (STS), and unmanaged (UNM) study areas (n = 593 logs). Error bars represent the standard error of the mean. STS is statistically different from the UNM, but SGS is not statistically different from UNM. Data from experimentally harvested northern hardwood sites in the Bartlett Experimental Forest in Bartlett, NH. Error bars show ±1SE.

Downed-Woody Debris Decay & Diameter Classes

We plotted decay classes and diameter classes against volume for all three harvest treatments. We found that SGS and UNM treatments had the greatest volume of DWD in decay classes 1, 2, and 3 while decay classes 4 and 5 were scarce in our three harvest treatments. Within the STS harvest treatment, the volume of DWD was nearly evenly distributed across all three decay classes (Figure 14). We also chose to plot diameter classes of DWD against volume for all three harvest treatments (Figure 15). Our data show that within the STS harvest treatment, DWD volumes were evenly distributed across all four diameter classes, while SGS and UNM has more variability. Within the SGS harvest treatment, the greatest volume of DWD was found in the 15.1-25.0cm class.

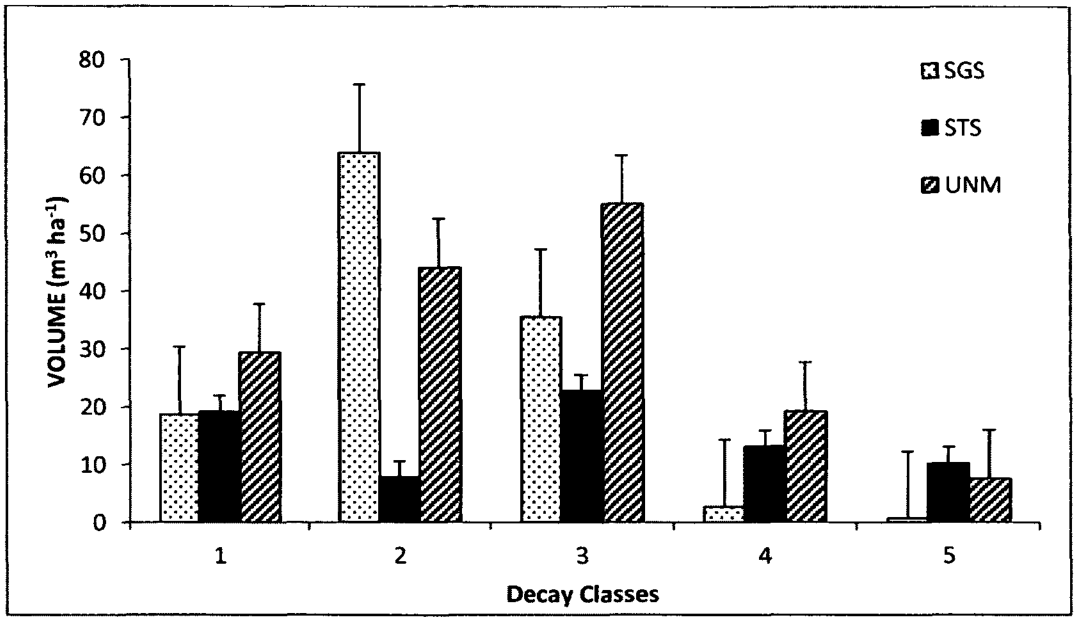

Figure 16. Volume of downed woody debris within each decay class for the small-group selection (SGS), single-tree selection (STS), and unmanaged (UNM) study sites in the Bartlett Experimental Forest in Bartlett, NH. Error bars represent ±1SE.

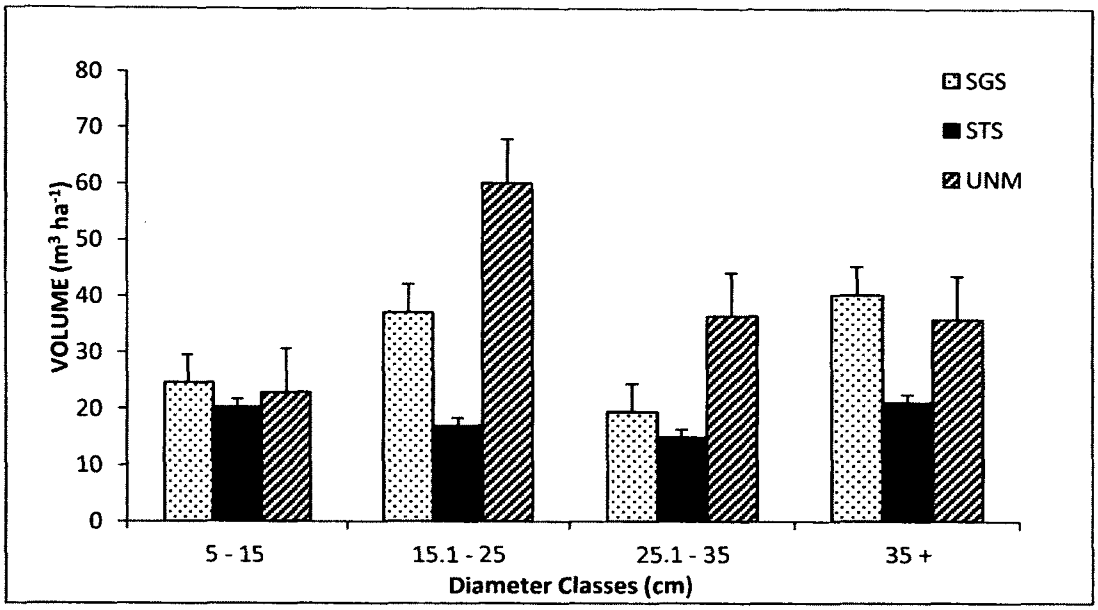

Figure 17. Volume of downed woody debris within four diameter classes for the small-group selection SGS), single-tree selection (STS), and unmanaged (UNM) study areas in the Bartlett Experimental Forest in Bartlett, NH. Error bars represent ±1SE.

Discussion

Concern for forest conservation and ecological sustainability are critical in modern forest management. Important ecological factors are being evaluated together economic factors in an integrated assessment of the future sustainability of forest management practices. Although species composition and diversity has previously been the central focus of conservation and sustainability efforts, other considerations are beginning to carry more weight. In particular, downed woody debris (DWD), is becoming a fundamental focus in assessing the sustainability and conservation of forest management, and for good reasons. DWD has long been valued for its importance to wildlife habitat (Bunnell and Houde, 2010), but it can also affect biological, physical, and chemical processes (Kirby et al., 1998) including soil processes, soil fertility, and hydrology (McCarthy and Bailey, 1994).

Since DWD abundances can be markedly affected by timber management practices, and is often not abundant on managed forest landscapes, the presence or absence of DWD is an obvious concern. In the northeast, many studies have quantified the effects DWD has on amphibian (Todd et al., 2009), song bird (Whelan and Maina, 2005), and small mammal (Bowman et al., 2000) populations. Over the past decades, these types of studies have included work on managed forests, comparing the effects of DWD and harvesting on the above populations, distributions, and genetic connectivity.

A component of research, however, that is missing in the northeast is quantifying how much DWD is on managed and unmanaged forests and how this varies by harvest treatment. These same quantification studies were missing in the central Appalachian region until 1994 when McCarty and Bailey (1994) addressed this knowledge gap by quantifying the amount and type of DWD within different management regimes. Our research goals seek to do the same. We seek to quantify the amount of DWD in three forested landscapes – unmanaged, SGS, and SGS treated areas in northern hardwood forests. Ultimately, we hope this information can be used to help landowners make informed decisions about their treatment options.

We hypothesized that the volume and density of DWD would be greatest in the unmanaged forest, followed by SGS and finally the STS treatment. Overall, our general hypotheses were met. We found that SGS most closely replicated the amount and volume of DWD found in the unmanaged area while the STS had significantly lower densities and volumes of DWD. This was an unsurprising result because management removes trees before they senesce, preventing most trees from falling to the ground and decaying. This finding concurs with studies that have come before ours – where managed landscapes were found to have far less DWD than managed landscapes.

Despite our data confirming our expected outcomes, there are additional explanations for why we saw significantly less DWD in the STS harvest treatment. The most obvious reason is that these low volumes and densities are a function of the type of treatment. STS removes individual trees in a process that allows managers to be more selective about the trees removed. Therefore, STS is often capturing mortality before it happens. This is not the case within the SGS treatment, where groups of trees are removed. This removal process limits the mangers capacity to target specific trees, preventing harvesting outside of these small groups. The areas in-between groups are subject to the same forces unmanaged stands are until they are harvested at a later date. In our study, nearly half of the SGS area has not been harvested. The non-harvested areas have large trees that are susceptible to the same natural forces experienced in the unmanaged stand. These findings pose an interesting paradox. Although STS replicates the normal individual tree fall disturbance patterns typical of unmanaged forests, it does not replicate the same amount of structural diversity (e.g., downed woody debris) that unmanaged forest typically do.

Contrary to what we found, one study cited that environmental disturbances can impact the amount of DWD. For example, pest and disease outbreaks can cause differential mortality within a stand, adding to the DWD supply. This did not appear to be the case in our study area, despite beech bark disease being ubiquitous in the STS since the 1940s, but relatively rare in our SGS and UNM study areas. The extent to which all these disturbances, anthropogenic or natural, interact are quite complex and might be responsible for considerable variation across managed and unmanaged forest landscapes.

A particularly noteworthy feature of our data is the general lack of large logs (>35cm) and highly decayed wood (decay classes 4 & 5) across all three of our harvest treatments. Large decayed wood is a very important source of nutrient recycling and wildlife habitat (Harmon et al., 1986; Laiho and Prescott, 2004). Without intentional management to provide this resource, it can become limited in managed forested areas. We found the fewest amount of large decayed logs in the STS treatment, while the UNM and SGS had the greatest. We suggest that STS prescriptions consider leaving large old trees as a measure to provide this resource for wildlife and nutrient cycling.

In general, our data suggests that SGS is one treatment that can provide the volumes and densities of DWD similar to unmanaged forests. Conversely, STS seems to limit DWD abundances. The significant abundance differences we found in our study area should be a consideration for landowners seeking to maintain structural diversity during harvesting.

While in no way comprehensive, our analysis provides preliminary results which suggest that forest management can influence the amount of DWD. We also suggest that forest management can provide a means of enhancing DWD size and decay stage diversity across the landscape with careful planning.

Conclusion

We recognize that more research is required before making definitive statements about how selection silviculture can shape structural elements on northern hardwood forests. Regardless, future efforts should include research assessing how these silviculture prescriptions can affect DWD abundances through New Hampshire. Expanding this type of research throughout other regions of the northern hardwood forests would also be beneficial. We believe that greater attention should be paid to management of downed woody debris in northern hardwood forests, especially as greater emphasis is being placed on the long-term sustainability and diversity of forest management. While our research area is small, we hope landowners and forest managers will become aware of different DWD patterns created by different management techniques. We suggest that greater attention also be paid to active management that leaves large live trees to ensure supply of rare, large decayed DWD.

We also suggest that studies assess whether DWD patterns and trends exist across different harvest treatment. We also suggest that these results be evaluated along other economic and non-economic indicators of successful management, including return on investment, forest health, and environmental services.

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CONCLUSION

We found small differences between selection silviculture treatments with regards to the timber quality and abundance of downed-woody debris (DWD). In general, our research suggests that there are potentially slight differences between the two selection silviculture systems with regards to both economic and ecological outcomes. While both the single-tree selection (STS) and small-group selection (SGS) were associated with small improvements in tree grade over 60 years, these improves were not significant nor very large

. When we converted these trade grades to standing tree values, the SGS had greater standing tree values than the STS. However, the differences between the STS and SGS harvest treatments were not significantly different from each other or the unmanaged site. We hypothesize that one of the reasons we did not find large timber quality improvements was due to an abundance of small diameter trees. Many of our sample trees in the SGS had not yet reached minimum diameter requirements to be graded even though they were healthy, straight, defect free trees. We suggest that in another ten to twenty years, when these trees have had a chance to grow more, results on the effects of harvest treatment on timber quality might be clearer.

Though we did not find strong differences between the treatments with regards to timber quality, we did find significant differences in the abundance of DWD. The unmanaged and SGS treatments had the greatest amount of DWD in both volume and density. These findings were statistically significant. A particularly noteworthy feature of our data is the general lack of large logs (>35cm) and highly decayed wood (decay classes 4 and 5) across all three of our harvest treatments. These are important components for both wildlife (Harmon et al., 1986) and nutrient cycling (Laiho and Prescott, 2004). We believe both diameter and decay class of DWD should be important considerations during timber removal.

Limitations in our study design restrict the applicability of our results over large scales. We were only able to examine northern hardwood forests in the Bartlett Experimental Forest because most other areas do not have long-term inventory data that allow for this type of comparison. The timber quality and downed-woody debris trends we found in our study might not hold true for all areas nor all forest types. We caution against applying our findings broadly. Additional research is needed to determine if the results observed in our studies are witnessed elsewhere.

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APPENDIX A

Appendix A uses Forest Inventory and Analysis survey data to construct graphs showing landownership, land preferences, and land use types in New Hampshire.

Landowner types in New Hampshire

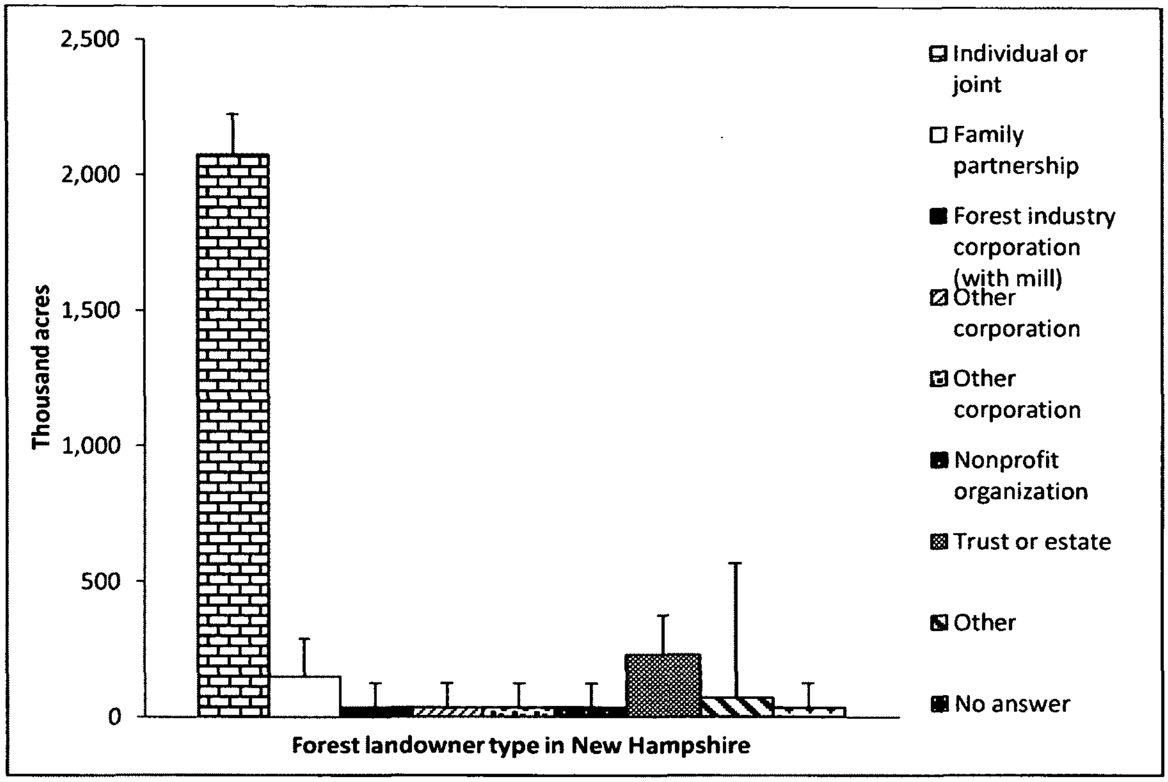

Figure 18. Landowner types in New Hampshire; derived from FIA survey data.

Source: FIA data. Family Forests: families, individuals, trusts, estates, family partnerships, and other unincorporated groups of individuals that own forest land. Where forest land is defined as land at least 10 percent stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. The minimum area for classification of forest land is 1 acre.

Questionnaire wording: "There are many different types of owners that hold woodland. How would you describe the type(s) of ownership(s) in which your [state] woodland is held?" Respondents were allowed to select more than one response.

Reasons for owning forested land for private ownerships in New Hampshire

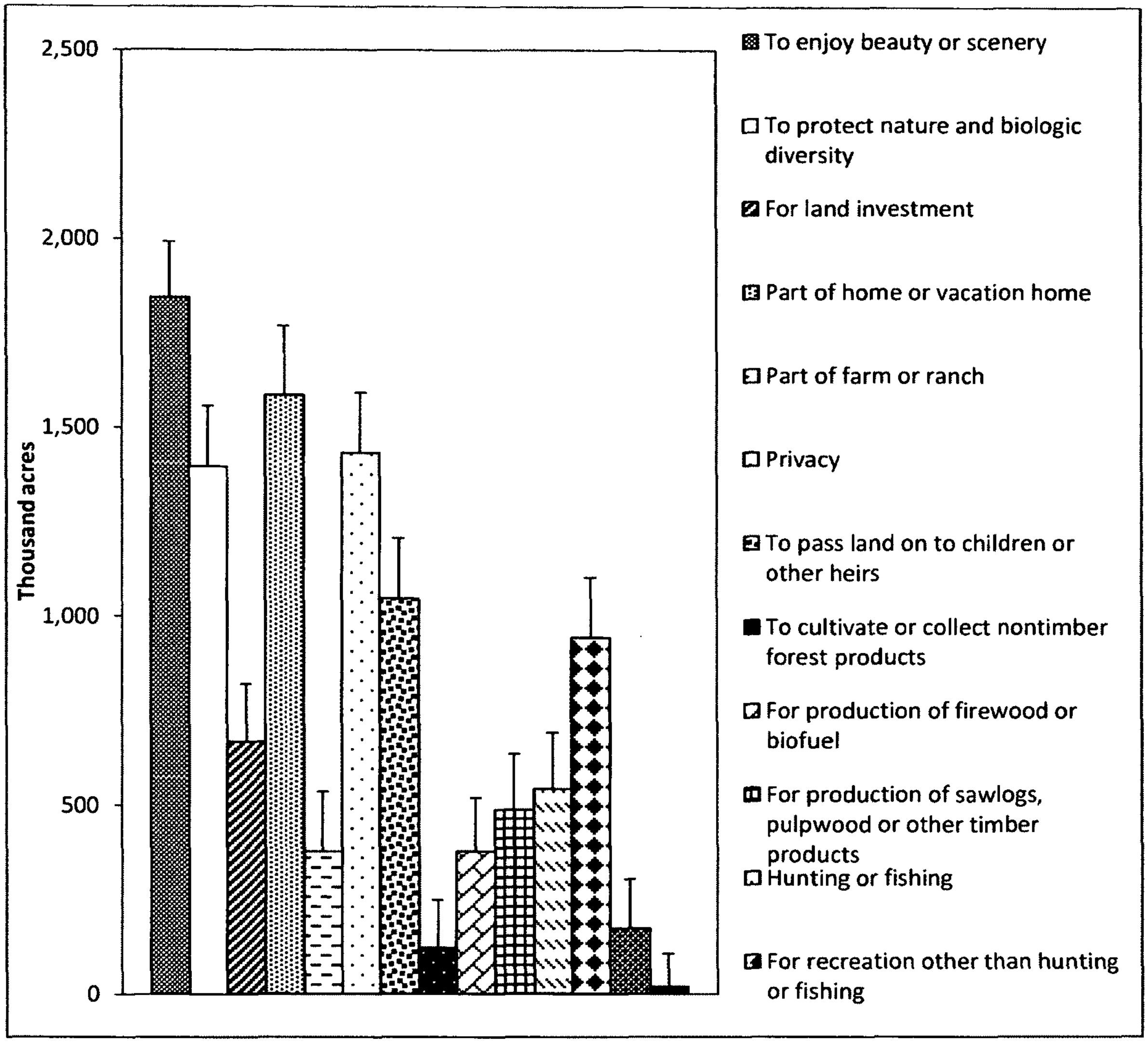

Figure 19. Reasons for owning forested land for private ownerships in New Hampshire; derived from FIA survey data.

Family Forests: families, individuals, trusts, estates, family partnerships, and other unincorporated groups of individuals that own forest land. Where forest land is defined as land at least 10 percent stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. The minimum area for classification of forest land is 1 acre.

Questionnaire wording: "People own woodland for many reasons. How important are the following as reasons for why you own woodland in New Hampshire?" Numbers include landowners who ranked each issue as a very important (1) or important (2) concern on a seven-point Likert scale.

Reasons for Timber Harvest in New Hampshire from FIA data.

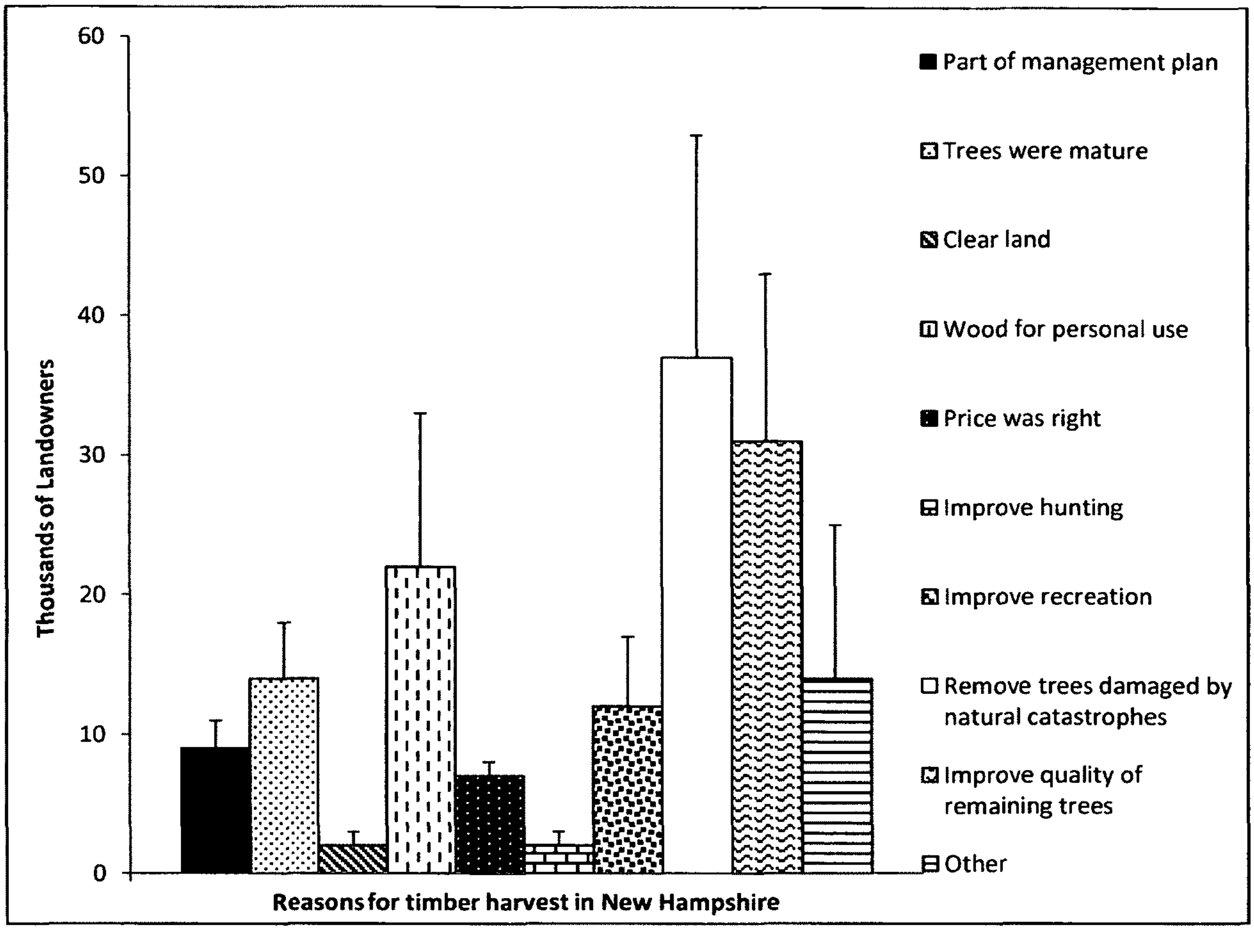

Figure 20. Reasons for Timber Harvest in NH; derived from FIA survey data.

Source: FIA data for New Hampshire landowners.

Owner type: Family forests: families, individuals, trusts, estates, family partnerships, and other unincorporated groups of individuals that own forest land. Where forestland is defined as land at least 10 percent stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. The minimum area for classification of forest land is 1 acre.

Questionnaire wording: If they have harvested or removed trees, they were asked: Why were trees harvested or removed? Respondents were allowed to select more than one response. Data collected from 2002-2006.

APPENDIX B

Hardwood market report prices from September 14, 2012.

Table 11. Hardwood market report prices from the September 14, 2012 issue. Kiln-dried gross tally prevailing market prices are used for standing tree value calculations. The range of market prices is shown in the right column.

Kiln-Dried Gross Tally		
Species	Prevailing Market Price (PMP)	Range
Ash	845	790-900
Aspen	585	540-640
Beech	685	620-730
Birches	1160	1070-1250
Hard Maple	1110	1040-1200
Soft Maple	1035	965-1125
Red Oak	910	830-970

Hardwood price index created from hardwood market report prices from September 14, 2012

Table 12. Hardwood price index created from hardwood price market reports. Calculations used to relativize standing tree values.

Species	Index (Gross Tally)
Yellow Birch	1.00
Hard Maple	0.96
Soft Maple	0.89
Red Oak	0.78
Ash	0.73
Beech	0.59
Aspen	0.50