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silviculture

Silvicultural Prescriptions Influence the Proportion of High-Quality Hardwood Butt Logs Harvested over a Half-Century of Management

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A long-term study on the Fernow Experimental Forest (FEF) in West Virginia provided an opportunity to test for differences in the timber quality of trees harvested from three silvicultural practices (HarvestType): diameter-limit, patch cutting, and single-tree selection. The effects of HarvestType and site index (SI) over time on the harvested proportion of trees with grade 1 butt logs within a compartment were tested using a repeated-measures linear mixed model. HarvestType*Time was a significant interaction ($P = 0.0018$) and SI had a slight positive effect ($P = 0.0036$). When examining the harvested proportion of grade 1 butt logs on a volume basis, the two terms were again significant ($P = 0.0003$ and $P = 0.0208$, respectively). The diameter-limit proportion of grade 1 butt logs consistently decreased while patch cutting and single-tree selection proportions consistently increase over time. Recent preharvest cruise data show a significantly greater residual proportion of grade 1 butt logs for single-tree selection compartments versus diameter-limit compartments on a per-tree and per-volume basis ($P = 0.0013$ and $P < 0.0001$, respectively). Results indicate that the production of grade 1 trees in diameter-limit harvests is not sustainable productivity wise whereas the single-tree selection harvests are. The sustainability of the production of grade 1 logs from patch cutting remains inconclusive.

Keywords: diameter limit, single-tree selection, patch cutting, tree grade, repeated measures

Owner preferences motivate the extent of forest management of hardwood forests. The National Woodland Owner Survey gives insights on the ownership objectives of the forest landowners who own more than half (55%) of the forested land base in the northeastern United States (Maine to West Virginia to Minnesota and Missouri; Butler 2008). Although timber harvest is considered an important objective by only 5% of responding forest landowners in the region, 66% of family forest acreage in the northeastern United States has undergone some type of harvest while under the control of the current owner(s) (US Department of Agriculture 2009). The proportion of private forests that have undergone harvests provides evidence that although forest landowners frequently consider nontimber objectives more important, the value of timber assets frequently gains importance when a financial need arises. Often, seemingly competing goals of income generation and continued forest cover (15.5% of respondents to Butler's survey list "to enjoy beauty or scenery" and 11.9% list "to protect nature and biologic diversity") lead landowners to choose partial harvest or uneven-aged silvicultural management. With high first-entry yields and easy implementation, exploitative harvests (e.g., diameter-limit [DL] cutting) occur on much of the privately owned forest in the northeastern United States (Nyland 1992, Fajvan et al. 1998). However, DL harvests are not considered silvicultural actions because little attention is paid to the residual stand or future forest productivity. One way to encourage landowners to implement silvicultural practices is by demonstrating that with well-planned forest management not only will yields improve over time but so too can timber quality and hence stand value.

The Forest Service (FS) tree grades developed by Hanks (1976) are known to be good predictors of the relative value of trees that will be harvested for conversion into lumber. On average, grade 1 trees are larger in diameter, taller in merchantable height, and possess a higher proportion of long, clear sections of wood from which higher grade lumber can be recovered. As an example, composite lumber

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grade and volume recoveries for the six principal commercial timber species in West Virginia (northern red oak [*Quercus rubra* L.], white oak [*Quercus alba* L.], yellow-poplar [*Liriodendron tulipifera* L.], sugar maple [*Acer saccharum* Marsh.], red maple [*Acer rubra* L.], and black cherry [*Prunus serotina* Ehrh.]) were derived using information found in Widmann (2013) and the tables of Hanks (1976). A composite lumber price scale for these same species was developed based on dry lumber price (Hardwood Market Report). Using this West Virginia-based example, the lumber value recovered from tree grade 1 is estimated to be 1.7 times that of tree grade 2 and 3.1 times that of tree grade 3. Alternatively stated, the value of a grade 2 tree is only 0.59 times that of a grade 1 tree and a grade 3 tree only 0.32 times that of a grade 1 tree. For values such as these, once the proportion of tree grade 1 trees in the stand exceeds 0.37, the value of tree grade 1 trees will exceed the value of the remaining proportion of lesser grade trees. Using Forest Inventory and Analysis (FIA) data from the northeastern United States, the distribution of tree grades for sawtimber on forestland in 2013 showed that the volume of tree grade 1 timber was 28.8% for all species (FIDO version 1.5.1.05b; apps.fs.fed.us/fia/fido/index.HTML accessed on Jan. 26, 2015) whereas the tree grade 1 percentage for northern red oak was 35.7%. For West Virginia, these tree grade 1 proportions were higher (35.7% and 53.4% for all species and northern red oak, respectively). Therefore, much of the value in these stands is concentrated in grade 1 trees.

Despite the importance of understanding how forest management influences tree grade and, correspondingly, value, there have been few long-term studies to draw on for inference. In the Lake states, early work by Eyre and Zillgitt (1953) noted no reduction of tree quality in stands cut to 68% of the volume 15 years earlier. Erickson et al. (1990) found that a light improvement cut had the greatest gains in the proportion of grade 1 volume harvested. DL harvests with limits of 30 and 56 cm also demonstrated some increases in the volume of grade 1 trees cut (Erickson et al. 1990). A significant increase in tree quality occurred for an individual tree selection cutting (residual basal area of 17 m^2/ha) versus light (21 m^2/ha) and heavy (14 m^2/ha) individual tree selection cuttings and a control (Strong et al. 1995). In New England, improvement in residual stand tree quality on a per-tree and per-volume basis was shown for single-tree selection (STS; Leak and Sendak 2002) as well as for DL cuts (Sendak et al. 2000). In the Central Appalachians, improvement occurred in residual stand quality for multiple treatments in a 34-year study that included a commercial clearcut, two STS options, DL treatment, and a control treatment (Smith and Miller 1987). A shelterwood study conducted on the Monongahela National Forest reported no significant changes in tree grade 2–5 years after the shelterwood cut (Johnson et al. 1998). On the Fernow Experimental Forest (FEF), Wiemann et al. (2004) found that the residual percentage of grade 1 trees was greatest for STS versus DL and control treatments. On the Vinton Furnace Experimental Forest, a selection cut (residual basal area of 11 m^2/ha) resulted in greater percentages of grade 1 trees versus DL cutting (Brown et al. 2004). The study period length for these studies ranges from 2 to 48 years, with only two studies (Erickson et al. 1990, Leak and Sendak 2002) containing more than one posttreatment set of measurements. The remaining studies provide important results regarding treatment effects; however, with just one posttreatment measurement, they cannot provide an examination of trends of tree grade fluctuation over time.

A long-term study of three harvest practices (STS, DL, and patch cuts [PATCH]) on the FEF in West Virginia spanning 7 decades allowed us to test whether managing a stand for forest products under silvicultural prescriptions would, over time, result in greater yields of FS tree grade 1 butt logs, not only as residual trees (Wiemann et al. 2004) but also as part of the periodic harvests, a critical measure for getting landowners to use alternatives to the exploitive DL harvests often used. These three harvesting practices have cyclical cutting prescriptions and each retain a significant residual postharvest stand, creating interest in determining whether harvests and residual stand conditions are consistent over time. The primary objective of this study was to compare the proportion of trees with grade 1 butt logs for all species removed over time, across site quality, and between silvicultural practices. We hypothesize that the proportion of harvested grade 1 butt logs will show a decrease over time with DL harvests. A secondary objective is to examine the proportions of trees with grade 1 butt logs in the residual stands.

Methods

Study Area

Our study was conducted on the FEF in northern West Virginia (Figure 1; 39.03°N, 79.67°W). The FEF has been used for forest research since 1934 and is part of the Monongahela National Forest. The FEF is part of the Northern High Allegheny Mountain Subsection, Allegheny Mountains Section (M221Ba), and ranges in elevation from 530 to 1,115 mm above sea level with an average growing season of 145 days and 1,430 m of annual precipitation distributed evenly throughout the year (Pan et al. 1997). Species composition is classified as mixed-mesophytic (Braun 1950) with northern red oak, yellow-poplar, and sugar maple common on mesic sites (i.e., northern red oak site index [SI] $\cong$ 24) transitioning to chestnut oak (*Quercus prinus* L.) and red maple on sites with more xeric characteristics (i.e., northern red oak SI $\cong$ 18). When combined with well-developed soils found throughout the forest and the region, growth and yield potential are considered fair to excellent (Smith 1995).

Silvicultural Treatments

We compare STS, DL, and PATCH harvests on sites within a range of 18–24 for SI (Figure 1). Six sites were assigned to each treatment (n = 18), with 74 harvests conducted over the period of study. The STS prescriptions use q = 1.3 based on 5.08-cm diameter classes and only manage sawlog-size trees (diameter breast height [dbh] $\geq$ 27.9 cm). On SI $\leq$ 20 sites, a 15-year cutting cycle

Management and Policy Implications

The long-term research results from this study suggest that foresters and landowners interested in maintaining a supply of high-quality trees in the central Appalachian region should refrain from diameter-limit cutting. Single-tree selection provides a more positive long-term benefit for supplying high-quality trees. Patch cutting also shows the possibility of being a positive alternative if current trends persist, but because of the incomplete conversion cycle from switching from even-aged to uneven-age management and the need for continued monitoring of the current study, a neutral response is necessitated.

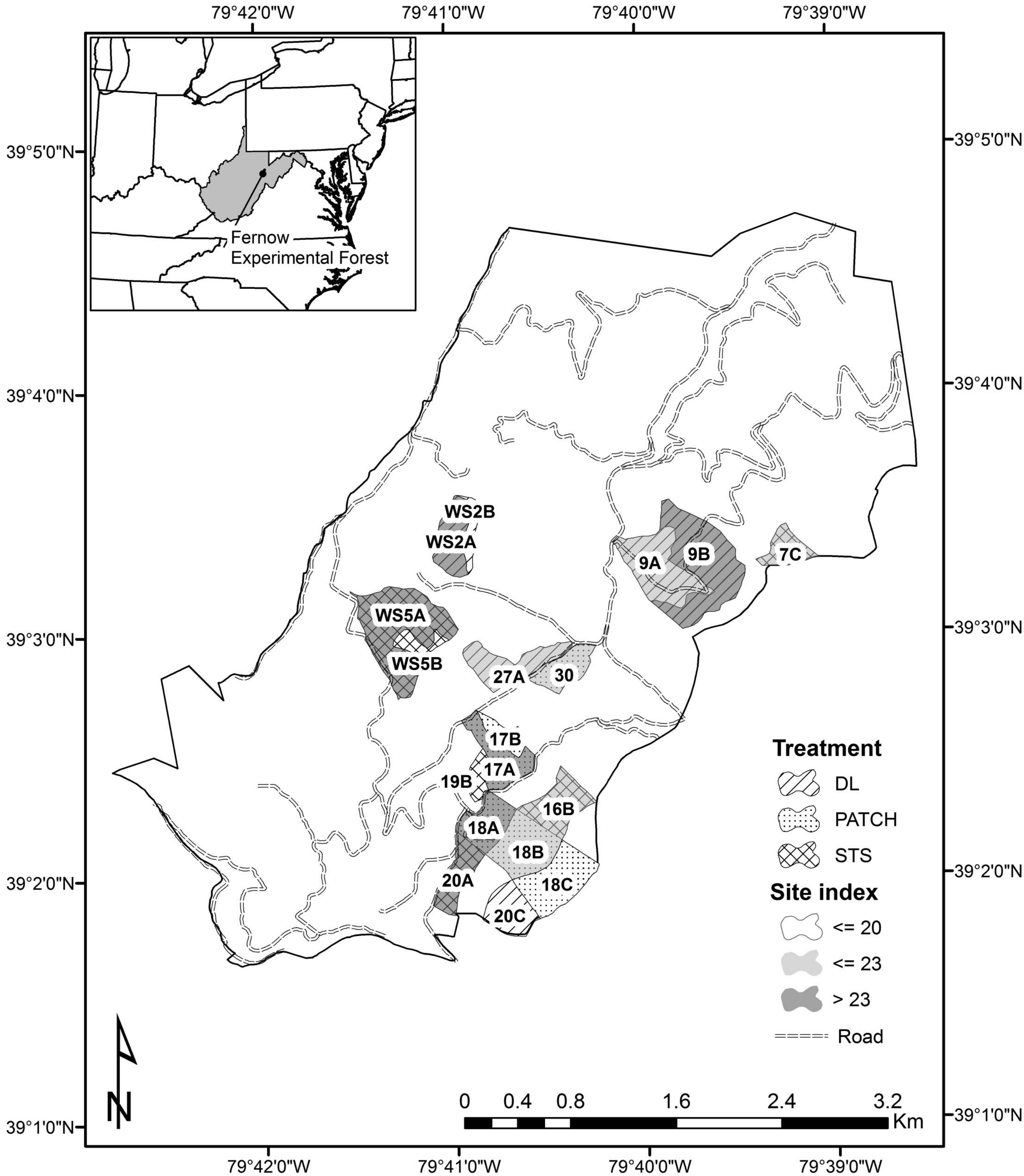

Figure 1. Location of Fernow Experimental Forest and study compartments.

was used with largest tree to grow of 50.8 cm dbh and a residual basal area of 8.0 m^2/ha for sawlog-size trees. The cutting cycle was 10 years on the remaining sites. On sites where $20 < SI \leq 23$, the largest tree to grow was 66.0 cm dbh and the residual basal area of sawlog-size trees was 11.5 m^2/ha. On sites where $SI > 23$, the largest tree to grow was 81.3 cm dbh and the residual basal area of sawlog-size trees was 14.9 m^2/ha. For the DL harvests where $SI > 20$, all trees with a dbh of 43.2 cm and larger were harvested on a 15-year cutting cycle. Otherwise, where $SI \leq 20$, a 20-year cutting cycle was used with the same minimum diameter limit to cut. PATCH prescriptions were made on a 15-year cycle on sites where SI ≤ 20 with an estimated rotation of 90 years for SI > 23. Where SI > 20 on PATCH sites, the cutting cycle was 10 years with either an estimated rotation of 70 years (where 20 < SI ≤ 23) or 80 years (where SI > 23). Total acres for each cut in the PATCH harvest were based on rotation length, number of periodic cuts, and study area size. Individual patch cuts removed approximately 0.16 ha, and all stems 2.54 cm dbh and larger were felled. In general, patches considered the "worst" in terms of tree quality or probability of reaching rotation age were harvested first for this study, with some short-lived and harvest-damaged trees removed from between patches.

Study compartments range from approximately 4 to 32 ha in size for a total of 242 ha, and management on all of these compartments began in the 1950s and continues to the present. The age structure of the original cohort was largely even-aged, with some residuals from before the initial harvest around 1910. Additional detail on study sites and silvicultural treatments can be found in a companion study addressing productivity and species composition (Schuler 2004).

Data

A grade was assigned to each tree marked for removal during the periodic harvests. US Department of Agriculture FS standards, codified by Hanks (1976), were used to assign grade, including the following for grade 1 butt logs:

- minimum dbh of 40.6 cm;
- a minimum clear length contained within the best 3.6-m-long section of the bottom 4.9 m of the tree of 3.0 m on the grading, or second-worst face; and
- less than 10% cull deduction.

Trees with dbh of at least 25.4 cm were assigned grades during both a preharvest and marked-for-cut (harvest) cruises. Harvest records from 1964 to 2013 were tabulated, and the proportion of grade 1 trees (P_{G1}) removed was calculated for each harvest on each compartment. The proportion of grade 1 volume (PV_{G1}) removed was also calculated.

$$P_{G1} = \frac{number\ of\ grade\ 1\ trees}{total\ number\ of\ gradable\ trees}$$

$$PV_{G1} = \frac{volume\ of\ grade\ 1\ trees}{total\ volume\ of\ gradable\ trees}$$

Volume data were generated from local volume tables based on dbh and reflect volume to a 10.16-cm top. Analyzing P_{G1} and PV_{G1} allows for comparisons to be drawn to previous studies and creates flexibility when local volume tables may be absent. Grade data from preharvest cruises from 1986 to 2013 were available and P_{G1} and PV_{G1} were calculated on a compartment and year basis. Preharvest cruises occurred in the same year as the harvest. These values represent the residual trees from the previous harvest and ingrowth of trees. Postharvest stand values for P_{G1} and PV_{G1} were calculated by subtracting the harvested trees from the preharvest cruise data. SI was recorded as height at base age 50 for northern red oak and is included as a covariate. The continuous variable Time is measured as the harvest year minus the year of first harvest in the experiment. It is found by subtracting 1964 from each harvest year.

Statistical Methods

Harvest methods are applied at the compartment level; therefore, harvested P_{G1} and PV_{G1} were calculated for each compartment. Some compartments may have had harvests in the same year, but harvests for each compartment generally occurred in different years and are thus irregularly spaced. Hypothesis testing was conducted within the framework of a linear mixed model (LMM). Repeated-measures analysis was conducted in SAS/STAT Version 12.3 using PROC MIXED with the REPEATED statement used to account for the repeated measures on each compartment over time. Because of the irregularly timed harvests across and within harvest types, some covariance structures are not suitable. The equation for this mixed model is

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\boldsymbol{\gamma} + \boldsymbol{\varepsilon}$$

where $\mathbf{y}$ is a vector where each element is the proportion of grade 1 trees or the proportion of grade 1 volume harvested from a compartment; $\mathbf{X}$ is a matrix consisting of values for HarvestType, Time, and SI for each compartment; $\boldsymbol{\beta}$ is the vector of the unknown fixed-effects parameters; $\mathbf{Z}$ is the known design matrix based on the selected covariance structure; $\boldsymbol{\gamma}$ is the vector of the unknown random-effects parameters; and $\boldsymbol{\varepsilon}$ is the unobserved vector of random errors.

Preliminary analysis began using HarvestType, SI, and Time as main effects and the two-way interactions HarvestType*Time and HarvestType*SI as the full model. The full model was estimated using each of the three spatial covariance structures (linear (sp(lin)), power (sp(pow)), and Gaussian (sp(Gau)); an unstructured covariance component; compound symmetry; and the variance components covariance structure. The model with the least Akaike information criterion corrected (AICc) value was selected as the best covariance structure. Modeling then proceeded to test interaction terms for significance with α set at 0.05. Because HarvestType is a categorical variable, pairwise comparisons were considered as the type of contrast for any multiple comparisons (MCs) of the different harvest types.

The interaction term of HarvestType*Time requires a fixed value of Time for MC testing because time in this case is a continuous variable. Rather than simply use the mean for Time, three temporal values were used: 15 years, 30 years, and 45 years. These values provide a finer resolution to examine changes over time than just the single mean value of Time and were chosen a priori. To maintain the familywise experimental error rate, α was divided by 3 using a Bonferroni adjustment (Neter et al. 1996) and the α level set at 0.01666 for each set of MCs conducted at the three temporal values. MCs were conducted using the option ADJUST=SIM (Edwards and Berry 1987) applied in the LSMEANS STATEMENT in SAS/STAT Version 12.3.

After fitting the model, diagnostic plots were produced to assess conformance to model assumptions. LMMs provide more flexibility in the covariance matrix for the error term as opposed to a general linear model. However, normality is still assumed for the error matrix. Normal probability plots did not show deviations from normality for any of the final models. Residuals were plotted against the fitted values to examine heteroscedasticity and supported the use of a linear model. Once the final models were fit with the best covariance structure type as indicated by AICc values, there was no further evidence of heteroscedasticity in the plots of residuals against the fitted values. This would have been an indicator that the linearity assumption was incorrect. Therefore, the use of a linear model was justified for these proportion data.

Table 1. Tests for main and interaction effects, harvested P_{G1} model.

Effect	df_1	df_2	F	P
HarvestType	2	39.2	40.26	<0.0001
SI	1	21.5	10.68	0.0036
Time	1	54	7.38	0.0088
HarvestType*Time	2	53.3	7.15	0.0018

Table 2. Tests for main and interaction effects, harvested PV_{G1} model.

Effect	df_1	df_2	F	P
HarvestType	2	43.2	18.57	<0.0001
SI	1	36.6	5.83	0.0208
Time	1	50.4	11.97	0.0011
HarvestType*Time	2	50.5	9.75	0.0003

The longitudinal models developed can also be used for forecasting. P_{G1} and PV_{G1} for the next-scheduled harvest for each compartment were estimated from the final models using the empirical best unbiased estimator (EBLUE) for $\hat{\beta}$ and the empirical best linear unbiased predictor (EBLUP) for $\hat{\gamma}$ (Littell et al. 1996). The EBLUP and EBLUE are substituted into the mixed-model equation and an estimate is generated for P_{G1} (or PV_{G1}) for the next harvest. This estimate for the next-scheduled harvest can also be used as a visual check for adherence to a linear model.

Because of insufficient repeated measures, it is not currently possible to statistically test temporal changes over time between treatments in tree grade for the residual stand. However, a limited examination of the last periodic inventory of each compartment does allow for a comparison between treatments. Hypothesis testing for residual P_{G1} and PV_{G1} was conducted as a LMM as before because of heterogeneity found in the harvest-type group variances. The variance components type was used as the covariance structure because there are not multiple measurements per compartment as in the previous analysis. There was no time component; only HarvestType and SI are factors in the model, with the interaction term HarvestType*SI included in the full model. Modeling proceeded by testing the interaction term for significance with α set at 0.05, followed by testing of the main effects. MCs were conducted using Tukey's test.

Results

Harvested P_{G1} Models

The sp(pow) structure had the lowest AICc value and was selected as the best-fitting covariance structure. The nonsignificant interaction term HarvestType*SI ($P = 0.46$) was dropped from the model, and the final model included the following terms: HarvestType*Time, HarvestType, Time, and SI. The P value for HarvestType*Time was 0.0018 and for SI it was 0.0036 (Table 1). The effect of SI was modest; a 1-m increase in SI results in an increase of between 0.007 and 0.032 in P_{G1}.

Residual P_{G1} Models

The nonsignificant interaction term HarvestType*SI ($P = 0.57$) was dropped from the model, as was SI ($P = 0.40$). Only HarvestType was significant ($P = 0.0017$).

Harvested PV_{G1} Models

For PV_{G1}, AICc for the sp(lin) covariance structure was least for the full model. The HarvestType*SI interaction term was not significant ($P = 0.35$), and the final model included HarvestType*Time, HarvestType, Time, and SI. The P value for HarvestType*Time was 0.0003 and for SI it was 0.0208 (Table 2). The effect of SI on PV_{G1} was slight; an increase of 1 m in SI increases the proportion from 0.003 to 0.030.

Residual PV_{G1} Models

HarvestType*SI was also nonsignificant in the residual PV_{G1} model ($P = 0.53$) and was dropped from the model. SI was again nonsignificant ($P = 0.50$). The final model included only HarvestType ($P = 0.017$).

Temporal Tree Grade Changes

The proportion of grade 1 trees harvested decreases on a number of trees basis (P_{G1}; Figures 2 and 3 and Table 1) and on a volume basis (PV_{G1}; Figures 4 and 5 and Table 2) for DL harvests over time. The grade data for the residual stands covers a more limited period of time—from the late 1980s to the present. P_{G1} and PV_{G1} for the residual DL stands exhibit constant proportions over time (Figures 6 and 7). One factor to consider is that because of the high minimum-cut dbh, trees are cut at harvest time only if they exceed 43.2 cm. Tree grade 1 requires a minimum diameter of 40.6 cm; therefore, nearly all potential grade 1 trees are cut at each harvest. In a summary of preharvest inventory data, we found that approximately 75–80% of trees are too small to grade as a 1. Only half of those trees become grade 1 trees as of the last set of DL harvests, which is approximately 10–12% of the stand (Figure 6). The decrease in harvested P_{G1} is masked by the small percentage of trees of potentially grade 1 size being heavily weighted by trees below 40.6 cm in the residual stand P_{G1} and PV_{G1} values. High site quality and the long harvest interval may also be factors. In addition, preharvest stands were not graded until the late 1980s, making subtle changes harder to illustrate.

Over time, harvested P_{G1} and PV_{G1} increased for PATCH harvests (Figures 2–5 and Tables 1 and 2). Until all of the patches have been cut once, trees from the original cohort of the stand will be part of each patch cut. As the compartments are fully converted to patch cutting, these older, larger trees will be harvested in the patch cuts. After cutting, each regenerated patch produces a small wave in the diameter distribution. The first patch cut wave in the overall stand distribution is separated from the original cohort's diameter distribution by a trough. The trough in the diameter distribution results from the separation in age of the original cohort and the first patch cut regeneration. As the original cohort patches are cut and regenerate, the trough in the diameter distribution is shifted to the larger-diameter classes as the regenerated patches age. When the trees in the first regenerated patch grow large enough to be gradable, they will be graded at the lowest grade because of dbh minimums on tree grades. Concurrently, the number of patches with original cohort trees will grow fewer. The residual stand P_{G1} will drop as the first patch cut reaches gradable size provided a major disturbance does not adversely affect the uncut patches. Residual PV_{G1} may also drop but will be buffered by the greater diameter of the grade 1 trees. Patches are also area controlled, and locally variable conditions may create variability in dbh and quality. There are several compartments with drops in residual P_{G1} and PV_{G1} (Figures 6 and 7) that may have occurred as a result of the factors mentioned.

Harvested P_{G1} and PV_{G1} increase over time for the STS compartments (Figures 2–5 and Tables 1 and 2). Residual P_{G1} and PV_{G1} in each compartment exhibit fluctuations around each compartment's postharvest proportion (Figures 6 and 7). In adhering to the

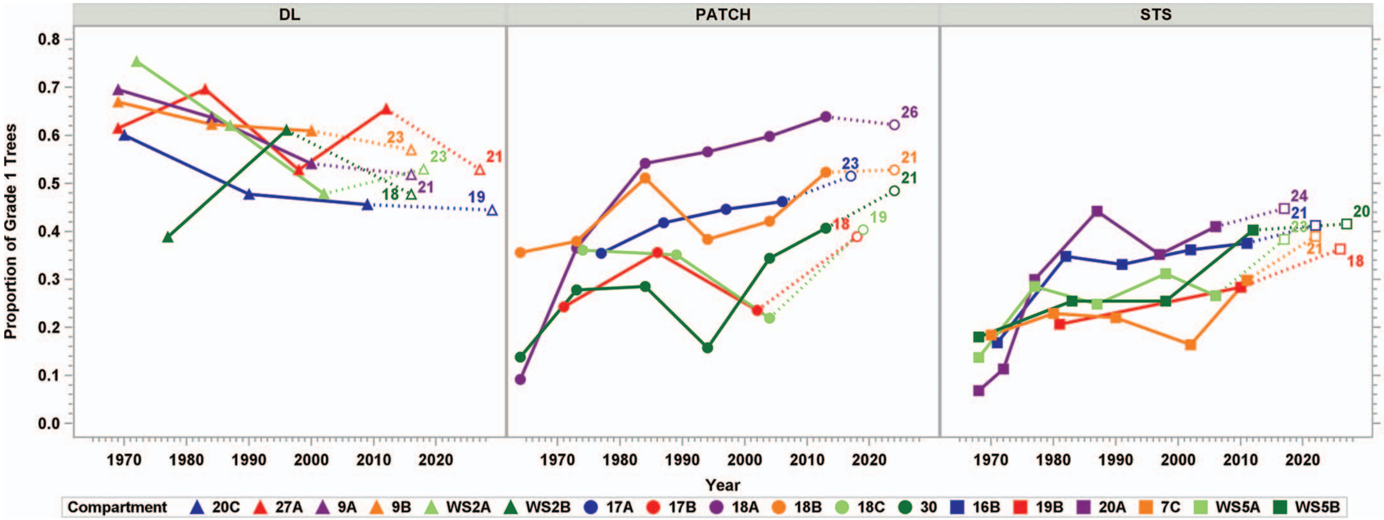

Figure 2. Proportion of grade 1 trees harvested over time for three harvest types. Open symbols and dashed lines are EBLUPs for the next-scheduled harvest. Each line is a compartment labeled by SI.

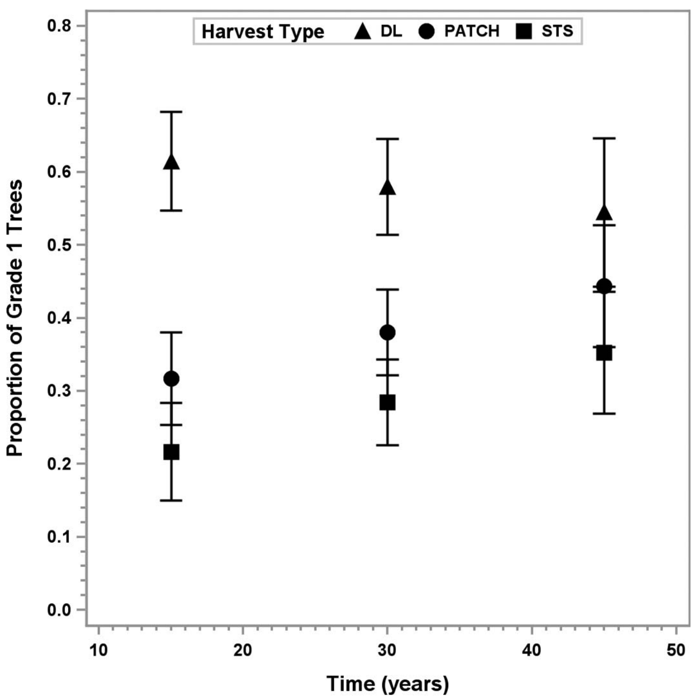

Figure 3. Estimated mean proportion of grade 1 trees harvested for three harvest types at 15-year fixed intervals. Bars indicate 95% confidence intervals.

q value for the STS prescription, trees throughout the stand may be cut, and harvested P_{G1} and PV_{G1} values are closer to the preharvest P_{G1} and PV_{G1} values. Again, the shorter time period covering available grade data from residual stand cruises does not fully illustrate the long-term changes that may have occurred in residual stand quality.

Most compartments, irrespective of harvest type, showed a recovery in residual P_{G1} and PV_{G1} after harvest and before the subsequent harvest. In general, P_{G1} and PV_{G1} for the residual stand were lower, but on occasion, they were slightly higher when P_{G1} and PV_{G1} for the harvest were lower than preharvest P_{G1} and PV_{G1}. Three PATCH compartments (17A, 18A, and 18C) decreased more than 0.1 in P_{G1} and PV_{G1} from one preharvest inventory to the next. Otherwise, there was general stability in the residual stands regarding P_{G1} and PV_{G1} within a harvest type.

P_{G1} Treatment Comparisons

DL harvesting had greater numbers of grade 1 trees removed in initial harvests (Figure 3), and this harvest type produced significantly greater proportions than the PATCH and STS treatments (Table 3) in years 15 and 30. The estimated mean ($\overline{P}_{G1}$) for DL harvests was between 0.55 and 0.68 at 15 years (Figure 3). The estimated difference in $\overline{P}_{G1}$ was between 0.21 and 0.39 for DL versus PATCH and 0.30 and 0.49 for DL versus STS in year 15. In year 30, the estimated difference in $\overline{P}_{G1}$ had dropped to between 0.11 and 0.29 for DL versus PATCH and between 0.21 and 0.38 for DL versus STS. At year 15, the PATCH versus STS difference in $\overline{P}_{G1}$ was not significantly different but was significant at year 30. However, the difference between the two was roughly the same at slightly greater than 0 to 0.20, suggesting mean proportions were nearly parallel during the two periods.

At year 45, the DL and PATCH treatments were not significantly different for $\overline{P}_{G1}$, nor were the PATCH and STS treatments (Table 3). The DL and STS treatments were still significantly different with $\overline{P}_{G1}$ still between 0.06 and 0.32 higher for the DL treatment. However, treatment proportions are converging over time (Figure 3). Although the PATCH and STS proportions are increasing, the DL proportion is decreasing. Five of six forecast proportions for the next DL harvest are lower than the last recorded harvest, whereas five of six of the PATCH and four of six STS harvests are higher than their last record for each compartment (Figure 2).

Residual $\overline{P}_{G1}$ was only significantly different between DL and STS compartments (Table 4). $\overline{P}_{G1}$ for STS was from 0.04 to 0.14 greater than in the DL harvest compartments. There was wide variability in PATCH residual $\overline{P}_{G1}$ (Figure 8), most likely due to the PATCH compartments having not completed a full cycle of cutting in all of the patches.

PV_{G1} Treatment Comparisons

At year 15, $\overline{PV}_{G1}$ was greatest for DL harvesting (Figure 5) and was significantly different from PATCH and STS ($P < 0.0001$;

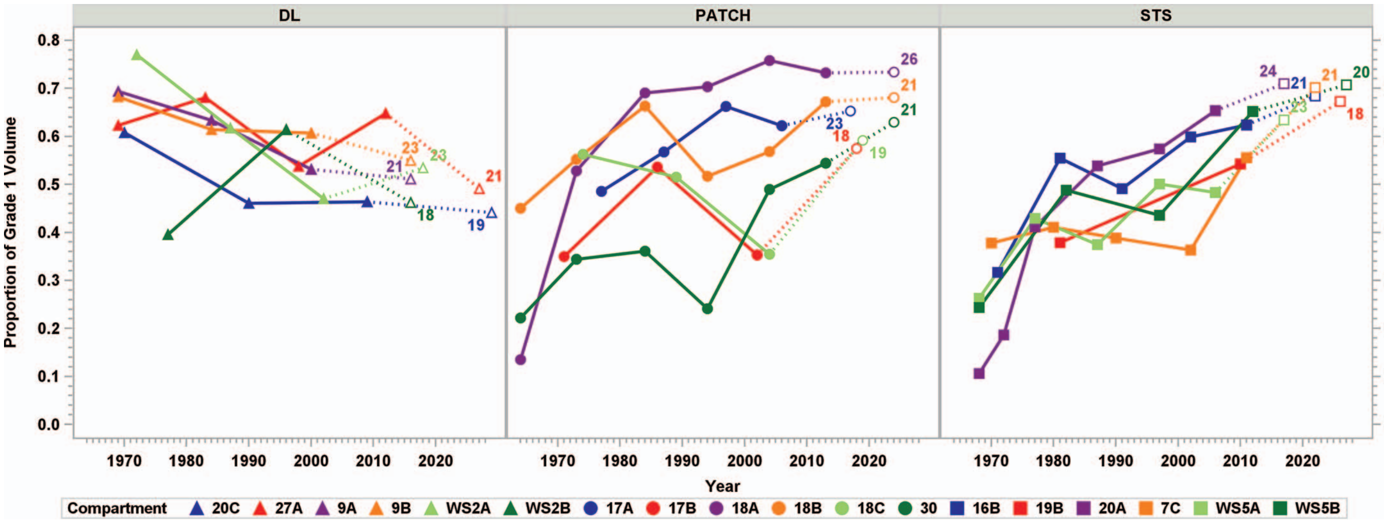

Figure 4. Proportion of grade 1 volume harvested over time for three harvest types. Open symbols and dashed lines are EBLUPs for the next-scheduled harvest. Each line is a compartment labeled by SI.

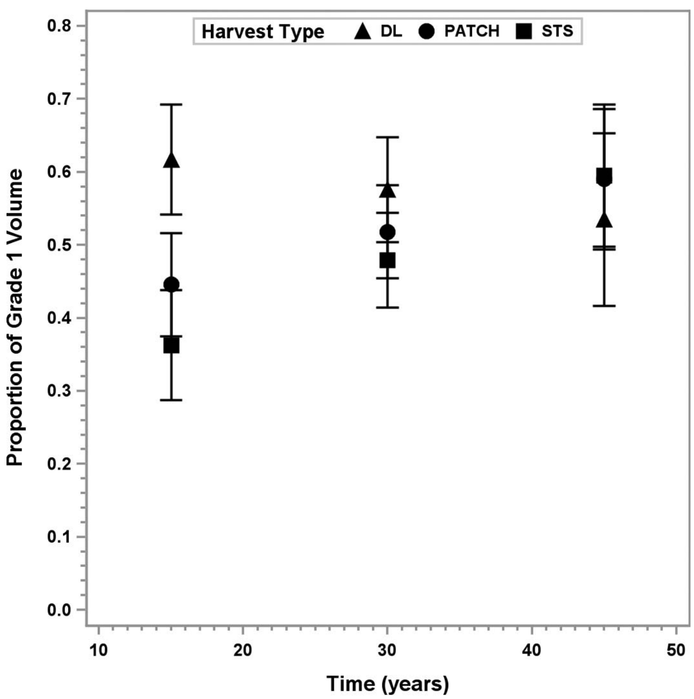

Figure 5. Estimated mean proportion of grade 1 volume harvested for three harvest types at 15-year fixed intervals. Bars indicate 95% confidence intervals.

Table 5). $\overline{PV_{G1}}$ was from 0.05 to 0.29 higher for the DL harvest versus PATCH and from 0.13 to 0.38 higher than STS. There were no statistical differences between any of the harvest types at years 30 and 45 (Table 5). PV_{G1} decreased for DL harvests but increased for PATCH and STS harvests (Figure 5).

Most compartments generally show recovery to preharvest PV_{G1} levels subsequent to the next harvest except Compartments 17A and 18A (Figure 7), which show moderate drops. Five of six DL compartments had a decrease in PV_{G1} predicted for the next harvest, whereas EBLUP's for all compartments in both the PATCH and STS treatments were greater than the last recorded harvest (Figure 4).

There was also a significant difference ($P < 0.01$) in residual $\overline{PV_{G1}}$ between the DL and STS compartments (Table 6). STS residual $\overline{PV_{G1}}$ was between 0.12 and 0.25 higher than the DL compartments. The pattern of wider variation showed again in the PATCH $\overline{PV_{G1}}$ (Figure 9).

Discussion

Important Considerations for Tree Grade

Using tree grade as a response variable requires some discussion of the characteristics of tree grades themselves. Trees can "improve" in quality (reflected by a numerically lower grade score) simply by reaching a diameter threshold over time. In addition, tree grade is an ordinal variable, not interval, and as such it is not appropriate to compute an average tree grade for a sample of trees. Any statistical techniques that model tree grade should account for the fact that it is an ordinal measure. Caution is needed when considering past studies in which tree grade was averaged. If the grade proportions are available, then these can be examined instead. If not, then there is still some information available. Noting that the lower grade number signifies better quality, if there is a change in a published "average tree grade," then this does indicate a directional change in quality. This is true because a change in the proportions of trees in each grade will move the "average tree grade" up or down. For instance, consider a reported average tree grade of 3.1. If a single tree improves in quality (i.e., a grade 2 tree changes to grade 1), then that average will decrease. If more trees improve their quality as opposed to decreasing, then the "average" will be lower, signifying an overall increase in quality. However, the statistical significance is unclear if the statistical procedure requires interval data.

The results from our study provide opportunities to examine temporal effects singly for each of the cutting practices as well as comparisons between silvicultural practices over time. Previous studies of tree grade do not always have a significant number of repeated measures or may not examine multiple treatments. However, our results can be compared to previous studies—sometimes temporally and sometimes by treatments.

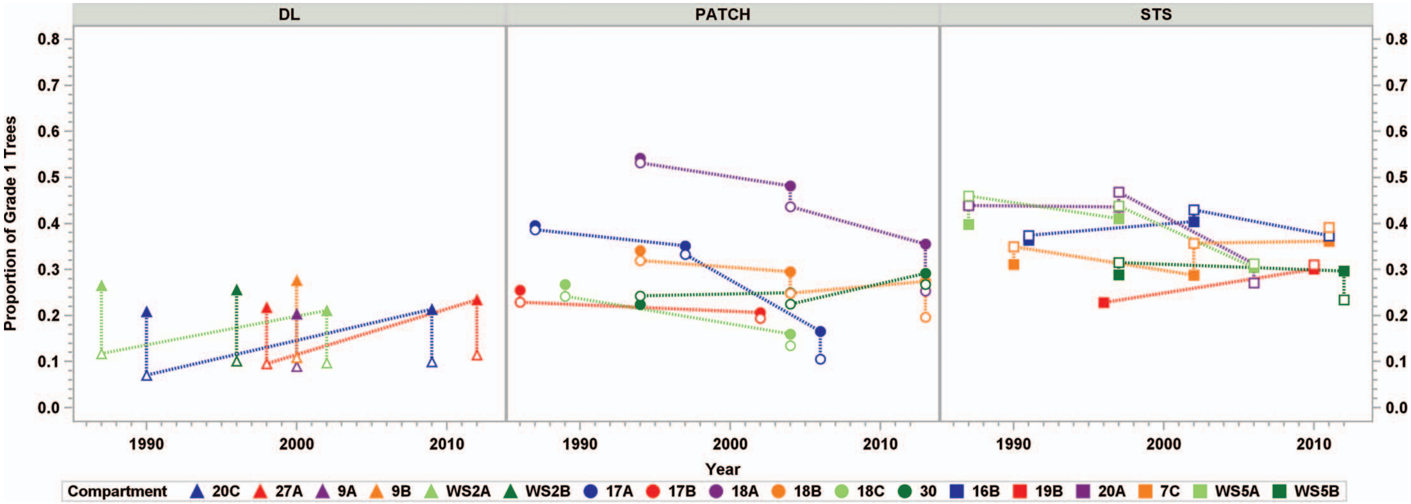

Figure 6. Proportion of grade 1 trees during periodic inventories (closed symbols) and for the postharvest stand (open symbols).

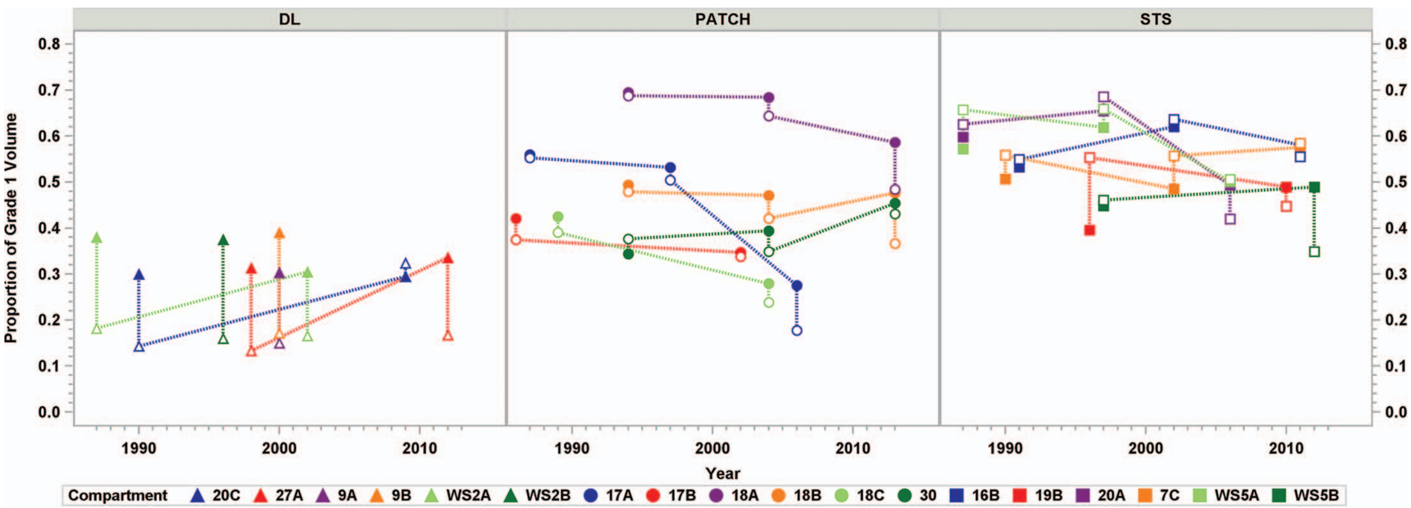

Figure 7. Proportion of grade 1 volume during periodic inventories (closed symbols) and for the postharvest stand (open symbols).

Table 3. Estimated pairwise difference in harvested proportion of grade 1 trees for three fixed time intervals, P_{G1} model (α = 0.0167 with Bonferroni adjustment).

Harvest type	Harvest type	SI	Time	Lower	Estimate	Upper	P
DL	**PATCH**	**21**	**15**	**0.2052**	**0.2981**	**0.3908**	**<0.0001**
DL	**STS**	**21**	**15**	**0.3030**	**0.3992**	**0.4934**	**<0.0001**
PATCH	STS	21	15	0.0082	0.1010	0.1924	0.0205
DL	**PATCH**	**21**	**30**	**0.1115**	**0.2000**	**0.2873**	**<0.0001**
DL	**STS**	**21**	**30**	**0.2074**	**0.2965**	**0.3827**	**<0.0001**
PATCH	**STS**	**21**	**30**	**0.0128**	**0.0965**	**0.1785**	**0.0118**
DL	PATCH	21	45	−0.0308	0.1019	0.2325	0.1467
DL	**STS**	**21**	**45**	**0.0607**	**0.1939**	**0.3230**	**0.0022**
PATCH	STS	21	45	−0.0274	0.0920	0.2094	0.1403

Note: Bolded values indicate statistically significant differences.

Table 4. Estimated pairwise difference in residual P_{G1}.

Harvest type	Harvest type	Lower	Estimate	Upper	P
DL	PATCH	−0.1119	−0.0099	0.0922	0.9545
DL	**STS**	**−0.1421**	**−0.0925**	**−0.0428**	**0.0013**
PATCH	STS	−0.1850	−0.0826	0.0198	0.1086

Note: Bolded values indicate statistically significant differences.

Comparisons—Temporal

Several studies have examined the effect of time on tree grade within specific silvicultural treatments. STS has demonstrated increases in the quality of residual trees over time on the FEF (Trimble 1970, Smith and Miller 1987, Wiemann et al. 2004), in Michigan (Erickson et al. 1990), in Wisconsin (Strong et al. 1995), and on the Bartlett Experimental Forest in New Hampshire (Sendak et al. 2000, Leak and Sendak 2002). Coincident increases in residual tree quality under DL are also demonstrated in each of these studies with the exception of Trimble (1970) and Leak and Sendak (2002), which did not have DL treatments. The increases in grade over time reported by Strong et al. (1995) and Sendak et al. (2000) for both DL and STS are each based on average tree grades; therefore, the aforementioned issue regarding averaging of categorical variables applies. In our study, observed postharvest residual stand quality generally recovers to preharvest levels over time for STS and DL when considering either P_{G1} (Figure 6) or PV_{G1} (Figure 7). Smith and Miller (1987) noted this pattern as well when measuring the volume of quality trees. No studies of changes in tree grade for patch cutting exist.

In addition to residual tree grade distributions, Erickson et al. (1990) report harvest data that include grade volumes over time. Lack of replication precludes statistical testing, but some increases in harvested PV_{G1} occur for DL and STS from 1957 to 1980. The final measurement year 1988 was affected by the salvage cut for elm undertaken in 1980. Our findings differ regarding DL harvests, which show a statistical decrease in harvested PV_{G1} but are similar for STS, where a statistically significant increase occurs over time.

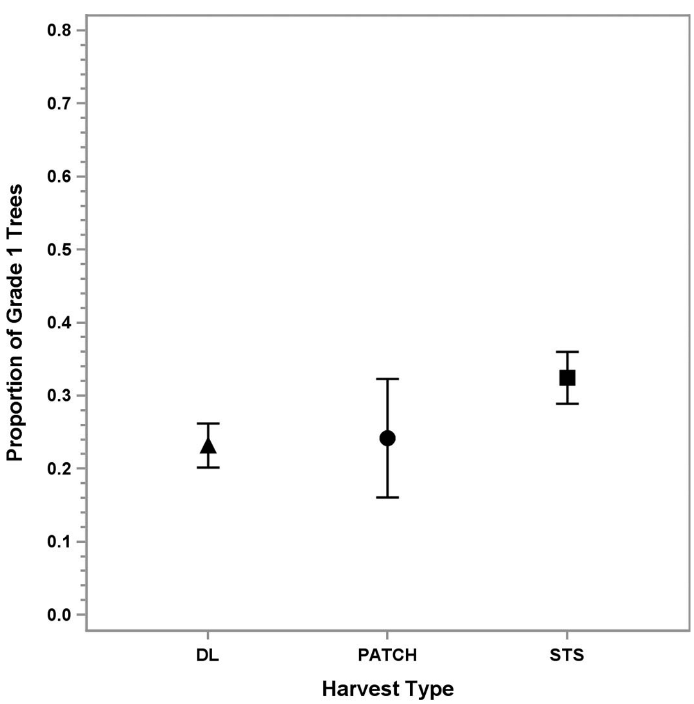

Figure 8. Estimated mean proportion of grade 1 trees at last periodic inventory. Bars indicate 95% confidence intervals.

Comparisons—Silviculture

As noted earlier, several studies included comparisons between silvicultural treatments. Elsewhere on the FEF (Smith and Miller 1987), two STS treatment plots, one of which included additional poletimber harvesting for cordwood and fuelwood, had higher percentages of residual stand grade 1 and 2 trees than the DL treatment. However, the STS treatment without the poletimber harvesting had percentages close to the DL treatment. Our findings for residual P_{G1} and PV_{G1} show that STS was significantly greater than DL (Tables 4 and 6). In another FEF study, two compartments included in our study, one DL and one STS, were sampled in a previous study on the effects of management on tree and wood quality (Wiemann et al. 2004). Unlike our analysis involving the proportion of grade 1 trees removed through harvest, the 2004 study assessed the grades of standing trees remaining after harvest but did not include an analysis of harvested P_{G1}. Wiemann et al. (2004) found that the percentage of residual grade 1 red oak, yellow-poplar, and sugar maple trees was highest after STS management and lowest after DL management (43% versus 23%). These measurements occurred in years not covered in the compartment periodic inventory and harvest cruises and they coincide with our values found for those compartments (Figure 2). Our findings of increases in P_{G1} and PV_{G1} over time in STS harvests, versus decreases in P_{G1} and PV_{G1} in DL harvests and the static levels in residual P_{G1} and PV_{G1} in DL, show that a quality loss is occurring with DL harvesting versus STS. In addition, although there are only small changes in residual PV_{G1} for DL and STS on a compartment basis, the overall level of PV_{G1} for STS stands is markedly greater (Figures 7 and 9 and Table 6).

A study in Michigan included four DL cutting treatments, DL-22, DL-16, and DL 12, and D-5, with minimum cut diameters of 55.9, 40.6, 30.5, and 12.7 cm, respectively, over 32 years (Erickson et al. 1990). There were also three STS treatments, BA-90, BA-70, and BA-50, which had residual basal areas of 11.5, 16.1, and 20.7 m^2/ha, respectively, for trees with dbh > 25.4 cm. Our study used a 43.2-cm DL; therefore, the DL-16 treatment is the best comparison level from the Erickson et al. (1990) study. Their STS BA-70 and BA-50 treatments are most similar to ours. The harvested PV_{G1} for DL-16 fluctuated lower and then higher over time but decreased to 0.27 in 1988 from 0.32 in 1957 whereas the harvested $\overline{PV_{G1}}$ for DL in our study has statistically decreased to 0.54 from 0.62 for a comparable 30-year period using years 15 and 45 (Figure 5). The Michigan study also included STS treatments, and all of those show increases in PV_{G1} over time (excluding the 1980 salvage cut). This is comparable to the STS treatment on the FEF where the mean P_{G1} increased from 0.36 to 0.59 over the 30 years examined in the MCs (Figure 3).

Table 5. Estimated pairwise difference in harvested proportion of grade 1 trees for three fixed time intervals, PV_{G1} model ($\alpha = 0.0167$ with Bonferroni adjustment).

Harvest type	Harvest type	SI	Time	Lower 95% confidence limit	Estimate	Upper 95% confidence limit	*P*
DL	**PATCH**	**21**	**15**	**0.0529**	**0.1712**	**0.2895**	**0.0004**
DL	**STS**	**21**	**15**	**0.1316**	**0.2542**	**0.3767**	**<0.0001**
PATCH	STS	21	15	−0.0358	0.0830	0.2017	0.1211
DL	PATCH	21	30	−0.0524	0.0580	0.1684	0.2962
DL	STS	21	30	−0.0138	0.0971	0.2081	0.0402
PATCH	STS	21	30	−0.0651	0.0392	0.1434	0.5308
DL	PATCH	21	45	−0.2320	−0.0553	0.1215	0.6428
DL	STS	21	45	−0.2368	−0.0599	0.1169	0.5957
PATCH	STS	21	45	−0.1632	−0.0047	0.1539	0.9961

Note: Bolded values indicate statistically significant differences.

Table 6. Estimated pairwise difference in residual PV_{G1}.

Harvest type	Harvest type	Lower 95% confidence limit	Estimate	Upper 95% confidence limit	*P*
DL	PATCH	−0.2317	−0.0692	0.0933	0.4436
DL	**STS**	**−0.2547**	**−0.1877**	**−0.1207**	**<0.0001**
PATCH	STS	−0.2811	−0.1186	0.0440	0.1443

Note: Bolded values indicate statistically significant differences.

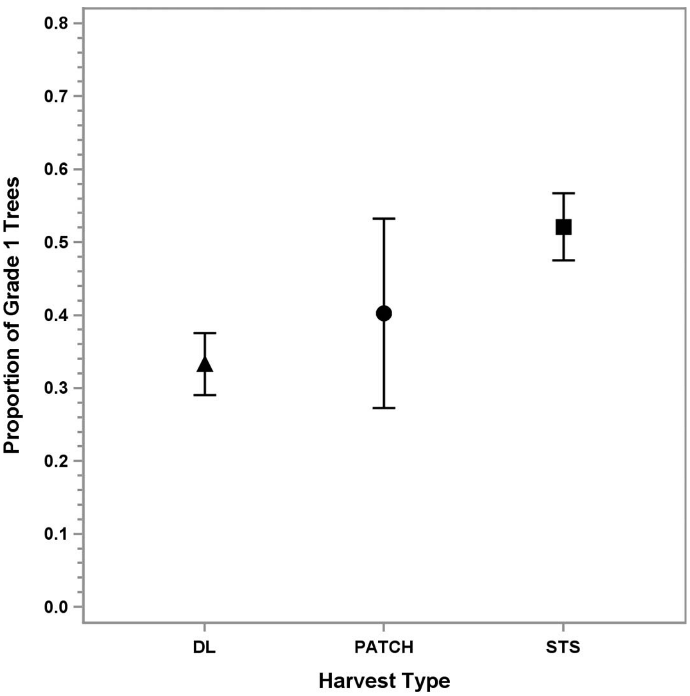

Figure 9. Estimated mean proportion of grade 1 by volume at last periodic inventory.

The significant HarvestType*Time interaction term and subsequent multiple pairwise comparisons over time have shown significant mean differences in our study. $\overline{PV_{G1}}$ has been significantly greatest in the DL treatment versus the PATCH and STS treatments at year 15. However, although the DL point estimate of $\overline{PV_{G1}}$ is seemingly greater at year 30, it is not significant, and at year 45 it is less than PATCH and STS but not significantly less. Considering Erickson et al. (1990) again, their DL-16 harvest PV_{G1} was greater than the BA-70 and BA-50 STS treatments in all years except the second cut in 1968, although no statistical tests were performed. It appears that although the two STS treatments have increased over time in their study, the two have not equaled or surpassed the slight decrease for the DL-16 treatment. In contrast, when comparing five cutting treatments, Niese et al. (1995) used volume change of estimated grade 1C or better lumber that could be produced from the harvested and residual trees over the period of 1971–91. Significantly greater volume for grade 1C or better lumber occurred in the following order: Light STS > Medium and Heavy STS > Control > DL. Direct comparisons by cutting practice of our results to other studies with similar practices may be complicated by differences in SI, the mix of species, and minor variations in the specific prescription within each type of cutting practice.

Conclusions

The results of our study demonstrate that DL cutting has removed higher statistically significant proportions of the best tree quality (grade 1) over time than STS and patch cutting. However, evidence suggests that this relationship is not steady in the long term because our hypothesis that proportions for DL cutting would show decreases was supported. Increasing proportions of grade 1 trees harvested from patch cutting and STS suggest a future reversal in rank for these two practices over DL harvests. Patch and STS have passed the midpoint of time required for complete conversion to their silvicultural prescription. By prescription, the residual stand structure in the DL compartments lacks trees with dbh greater than 43.2 cm and at the time of subsequent harvests the compartments are not recovering to prior harvest levels. The uninterrupted decrease shows a lack of sustainability productivity wise and a poor-quality high graded stand. Current preharvest cruises show that STS P_{G1} and PV_{G1} are roughly equal to harvest P_{G1} and PV_{G1}; therefore, they are sustainable productivity wise, with this relationship likely to continue through time.

When considering the PATCH treatment, the study's initial cohort still occupies approximately half of the area of the stand. Patch cut harvests are filling in behind this cohort, resulting in pulses of new trees. However, ongoing harvests continue to remove large older trees in patches that have higher proportions of grade 1 trees compared with the compartment-wide residual proportions. This is due to the new cohorts having trees that are not large enough to be considered for grade 1 but are still gradable. Once the entire area of the compartment has been cut, this older tree bias in harvested P_{G1} and PV_{G1} will be removed and residual and harvested P_{G1} and PV_{G1} are expected to stabilize. Because of the slightly higher harvest P_{G1} and PV_{G1} over the most recent preharvest P_{G1} and PV_{G1} in some compartments, it is not clear whether the production of high-quality butt logs will remain steady or increase in PATCH. Continued monitoring of the compartments will provide the information necessary to conclusively determine the long-term trends.

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