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Growth, yield, and financial return through six decades of various management approaches in a second-growth northern hardwood forest

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ABSTRACT

Evaluation of long-term studies provides information about the sustainability of forest management on a time scale valuable to forest managers. A long-term silvicultural study at the Argonne Experimental Forest in northern Wisconsin has been continuously maintained for over six decades, providing an opportunity to test differences in growth and yield between three partial cutting methods: single-tree selection, crop tree release, and diameter-limit cutting. Over 65 years, results showed that single-tree selection with low residual stocking (14 m^2 ha^{-1} basal area) performed best in regard to financial returns, growth, and yield, with high financial returns, greater levels of ingrowth, lower mortality, and greater residual percent volumes of high quality sawtimber. Diameter growth was maximized in low to moderate (17 m^2 ha^{-1} residual basal area) residual stocking selection. The diameter-limit cut (18 cm dbh limiting diameter) was not successful in producing high-quality trees or consistent yield. After 50 years the crop tree release treatment did increase percent of high-quality harvested volumes, but to a lesser extent than the selection treatments. Selection treatments removing more basal area provided an overall better return on investment, providing potential incentive for modification to traditionally practiced single-tree selection to higher residual basal areas.

1. Introduction

Sustainable forest management recognizes multiple-use values and incorporates both financial and ecological factors in order to meet biodiversity, sustainability, and economic objectives. Balancing growth and harvested yield is a common requirement of such objective-driven management, with the resulting sustained yield being both productive and economical (Leak, 1996). Testing sustainable forest management by assessing net growth with harvest yield and financial feasibility over the long-term is infrequently done, yet is needed to help management meet both sustainability and economic objectives. While some long-term studies assess one or more of these components, further research and continued monitoring are needed to identify compatibility between economic and ecological outcomes amongst changing conditions (Brown et al., 2018; Erickson et al., 1990; Niese et al., 1995; (Sinacore and Howard, 2015); Strong et al., 1995).

A key piece of sustainable forest management is selecting appropriate silvicultural systems for the forest type to optimize tree growth responses, with the outcome that volume accrues at an acceptable rate and growth is greater than mortality. Such silvicultural systems are typically classified as even-aged or uneven-aged, based in large part on the type of harvest-regeneration methodology used (Hann and Bare, 1979). Uneven-aged management generally controls density across different size classes to encourage recruitment along with uniform and consistent yield, while in even-aged systems, treatments tending different size classes (e.g., tending of older classes and encouragement of regeneration) do not occur simultaneously (Nyland, 1988).

Both even-aged and uneven-aged management methods have been recommended and work effectively in western Great Lakes northern hardwoods (Nyland, 1988; Tubbs, 1977). These forests are dominated by longer-lived, shade-tolerant sugar maple (*Acer saccharum* Marsh.), with lesser components of the moderately-tolerant yellow birch (*Betula alleghaniensis* Britt.), basswood (*Tilia americana* L.), and white ash (*Fraxinus americana* L.). Thinning can be a component in both methods to tend one age class, typically in even-aged systems. For instance, crop tree release, or free-thinning, in particular is a thinning method used in northern hardwoods that focuses on improving quality and growth rates of individual trees, taking advantage of the fact that residuals in thinned

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northern hardwoods stands grow faster than those in an unthinned control (Leak, 2007; Leak et al., 2014). Crop tree release favors specific crop trees using a combination of thinning criteria (Nyland, 2016), but thinning is most successful when the value increase of residuals is outweighed by the volume loss (Zeide, 2001), so evaluating the balance of growth, mortality, and volume yield is especially important in crop tree release treatments.

However, much uneven-aged management in northern hardwoods has predominantly focused on single-tree selection silvicultural methods with an empirical stand structure target (Arbogast, 1957; Eyre and Zillgitt, 1953). Single-tree selection is often propounded as the only advisable way to produce long-term sustained yield and continual quality improvement of residuals with a partial harvest method in uneven-aged northern hardwoods (Miller and Smith, 1993). Indeed, a wide array of research and practical application has shown that implementation of single-tree selection in hardwoods increases quality of both harvested and residual trees while ensuring consistent yield (Brown et al., 2018; Draper and Froese, 2021; Eyre and Zillgitt, 1953; (Leak and Sendack, 2002); Nyland, 1998). However, there have recently been increasing concerns about lack of regeneration, species diversity, recruitment, and the overall sustainability of the selection system in northern hardwoods (Campione et al., 2012; Hupperts et al., 2019; Previant, 2015). As a result, alternatives to traditional single-tree selection as conventionally applied (Pond et al., 2014) are being considered, and research in this area is limited (Campione et al., 2012; Danyagri et al., 2019; Henry et al., 2021; Matonis et al., 2011).

Diameter-limit cutting is one such alternative, being a widely used partial regeneration practice in northern hardwoods due to ease of application (Miller and Smith 1993, Schwartz et al., 2005). The method has been used to create two-aged or even-aged stands, or used as a one-time treatment with the intention to follow with more comprehensive forest management in the future (Trimble, 1971). Diameter-limit cutting is subject to substantial critique (e.g., Fajvan, 2006; Kenefic et al., 2005; Kenefic and Nyland, 2005; Nyland, 1988) as it implies a lack of attention to the residual stand. Poor quality residual trees may remain to accumulate growth, while stocking and structure receive no control. Thus, there is a missed opportunity to regulate stand development (Kenefic and Nyland, 2005; Miller and Smith, 1993). A key critique is that diameter limit cutting is often implemented solely for short-term economic gain (Kenefic and Nyland, 2005) and is indistinguishable from high grading. Published studies of repeat application of diameter limit cutting have shown mixed results in terms of yield and financial performance with some studies (e.g., Nyland, 2005) suggesting extremely poor outcomes while others (e.g., Buongiorno et al., 2000; Erickson et al., 1990; Smith et al., 1979) suggesting results depend on the diameter limit chosen. Severe low-threshold diameter-limit cuts provide few long-term sustainable quality improvements and economic benefits and have been associated with long-term failure in terms of sustainable yield and enhancement of ecologic conditions (Erickson et al., 1990; Nyland, 2005). In contrast, medium-intensity diameter-limit cuts (around 40 cm dbh) in northern hardwoods can consistently produce high quality trees by removing those having crossed the grade 1 diameter threshold (Draper and Froese, 2021). If implemented in conjunction with thinning or improvement below the diameter limit some drawbacks of diameter limit cutting may be ameliorated (Buongiorno et al., 2000; Erickson et al., 1990; Miller and Smith, 1993; Smith et al., 1979). Where applied in northern hardwoods, both diameter limit cuts and single-tree selection are assumed to lead to regeneration of tolerant and mid-tolerant species (Pond et al., 2014; Schwartz et al., 2005).

When selecting one these various management systems, a primary driving objective is economic success. Sustainable forest management incorporates a multiple-use and value approach to management, but changes in management are often not enacted without sufficient financial incentive. By extension, the need for growth to outpace mortality and harvested yield thus becomes both a sustainability and economic priority for forest managers. Long-term growth and financial analyses to evaluate this are especially important in long-lived, slow-growing forests such as sugar maple-dominated northern hardwoods. Tree quality in particular should be considered when evaluating long-term financial value of stands, as financial value in northern hardwoods sawtimber is strongly influenced by quality (Godman and Mendel, 1978). A main objective in northern hardwoods management is producing the highest quality sawlogs in the shortest time period (Leak and Yamasaki, 2012). Due to their necessity in meeting this goal and their influence on financial value, the metrics used to estimate quality in northern hardwood logs and standing timber, such as diameter, merchantable height, and percent cull, all become important indicators of the value of the stand, and more importantly, the value of produced yield. Management guides are often chosen with the objective of increasing sawlog volume production (Nyland, 2016), however established economic theory recognizes that increasing quality and consequently value of saleable removals will increase financial return, particularly when stand value and volume are not directly correlated (Lussier, 2009; Zobrist, 2014). In northern hardwoods both single-tree selection and crop tree release emphasize quality improvement of residuals (Kenefic et al., 2005; Leak et al., 2014; Nyland, 2016), but this improvement only translates to an increase in actual financial returns if those improved trees are removed at a later date (Trimble et al., 1974). Low-threshold (e.g. 20 cm or less) diameter-limit cuts do not encourage quality improvement of residuals and may not leave enough pole or smaller sawtimber-sized trees to allow for sufficient growth and improvement (Hough, 1954). Thus, silvicultural treatments that periodically remove all highest quality and large timber, while leaving pole and mid-sized intermediate quality growing stock, maximize financial value (Lussier, 2009; Reed and Mroz, 1997). Under financial analysis such management methods have demonstrably performed well (Erickson et al., 1990; Smith et al., 1979), but continual long-term evaluation is important.

Fortuitously, in the western Great Lakes region, several long-term studies have provided long-term financial analysis of various alternative management methods in northern hardwoods. Results show that medium-intensity diameter-limit treatments, as well as selection systems using relatively low residual basal area (11 m^2 ha^{-1}), outperform the selection treatments to high residual basal areas (18–21 m^2 ha^{-1}) that are widely regarded as appropriate, following Arbogast (1957) and other regional management guides (Bodine, 2000; Draper and Froese, 2021; Erickson et al., 1990; Reed et al., 1986). Also, when compared to higher residual basal area selection treatments, those with lower residual basal areas can result in greater post-harvest diameter growth, periodic growth, and lower mortality (Forget et al., 2007; Schuler and McGill, 2007) as well as greater total net growth, merchantable volume production, and higher species diversity ((Crow et al., 1981); Niese and Strong, 1992). Crop tree release also outperforms selection to 21 m^2 ha^{-1}residual basal areas in long-term (40-year) economic value and total volume yield (Niese and Strong, 1992); however, some heavier crop tree release treatments result in low rates of return and long-term (80-year) research recommends releasing no more than 50–100 crop trees per acre (Leak and Yamasaki, 2012). Crop tree release, diameter-limit cuts, and single-tree selection silviculture have been previously analyzed in conjunction with each other due to their prevalence in industry, public, and research forest ownership throughout the upper Great Lakes region (Schwartz et al., 2005).

A 65-year study at the Argonne Experimental Forest (EF) in northern Wisconsin provides an exceptional opportunity to analyze growth, yield, and financial return to determine the relative economic feasibility and sustainability of these partial cutting methods in second growth northern hardwoods. The applied single-tree selection and crop tree release treatments aim to increase economic value by improving quality and providing continual periodic return, whereas the low-threshold dimeter-limit cutting aims to extract economic value early and as soon as stock is available. Past research at this site suggested that if quality improvement and higher volume yield continued in selection treatments to lower residual basal areas, these would outperform other partial cutting

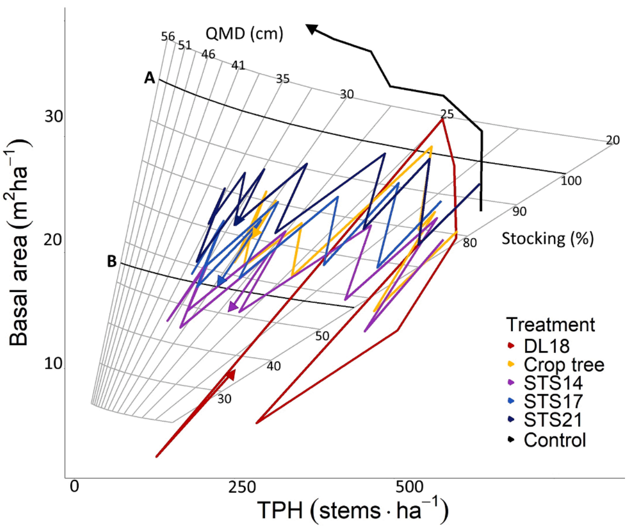

Fig. 1. Gingrich-style stocking chart for northern hardwoods (Gingrich 1971; Solomon and Hosmer 1987) with recommended maximum stocking (A-line) and minimum stocking (B-line). Directional lines indicate mean basal area, QMD, and stocking from 1951 to 2016 for each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. See section 2.2 for treatment code descriptions.

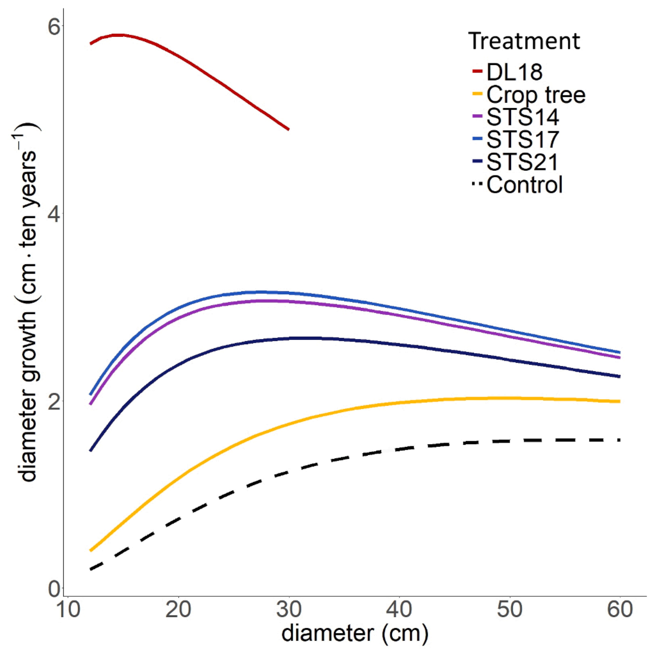

Fig. 2. Diameter increment model (population-average by treatment) with the natural log of the 10-year periodic change (2001–2011) in squared diameter predicted from the fixed effects $\frac{1}{dbh}$ and the interaction between treatment and $\frac{1}{dbh}$, with plot nested within treatment unit within block as a random effect. Conditional $R^2 = 0.375$, n = 824. Number of trees in each treatment were as follows: DL18, 79; Crop tree, 156; STS14, 109; STS17, 125; STS21, 134; Control, 221. Diameter growth modeled for each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. See section 2.2 for treatment code descriptions.

Table 1
Slope coefficients for the diameter increment model (population-average by treatment) with the natural log of the 10-year periodic change (2001–2011) in squared diameter predicted from the fixed effects $\frac{1}{dbh}$ and the interaction between treatment and $\frac{1}{dbh}$, with plot nested within treatment unit within block as a random effect. Values in a column followed by the same letter are not significantly different, $p < 0.05$. Number of trees in each treatment were as follows: DL18, 79; Crop tree, 156; STS14, 109; STS17, 125; STS21, 134; Control, 221 in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. See Section 2.2 for treatment code descriptions.

		Coefficient	
Term	Label	Estimate	Std. error
Intercept	*b0*	6.1374	0.221151
DL18	*b1*	−12.0367 *a*	3.769934
Crop Tree	*b2*	−43.4496 *b*	4.604848
Control	*b3*	−36.4214 *b*	4.400263
STS14	*b4*	−14.6390 *c*	4.519421
STS17	*b5*	−14.1288 *c*	4.363605
STS21	*b6*	−17.9689 *c*	4.491554

Table 2
Average plot dbh (cm) in 1951 (pre-treatment, ±1.1 cm), 1952 (post-treatment, ±1.0 cm), 2016 (4 years post-treatment, ±1.3 cm) in a cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. Means in a column followed by the same letter are not significantly different, $p < 0.05$, $n =$ 3. See section 2.2 for treatment code descriptions.

Treatment	1951	1952	2016
DL18	19.8 *a*	14.8 *b*	22.6 *c*
Crop tree	19.7 *a*	18.7 *ab*	29.0 *b*
STS14	19.9 *a*	19.0 *ab*	24.6 *bc*
STS17	21.5 *a*	20.9 *a*	27.7 *bc*
STS21	21.3 *a*	20.9 *a*	29.7 *ab*
Control	20.3 *a*	20.3 *a*	35.8 *a*

treatments after additional management (Niese et al., 1995; Strong et al., 1995). To evaluate the sustainability of the treatments both financially and biologically, we analyzed growth, mortality, quality, and yield, as well as financial performance. In the context of previous research, we anticipated quality improvements of residuals to be greatest in the medium selection treatment and crop tree release treatment, which would also translate to an increase in successful financial performance. Harvested volumes were expected to be consistently greater over the long-term for the lower residual basal area selection treatment. Greater ingrowth was expected in treatments that reduce basal area by larger degrees, including the 18 cm diameter-limit cut. However overall long-term growth, yield, and quality improvements were expected to be lowest in diameter-limit treatment. Diameter growth rates were anticipated to increase with lower densities (Erdmann and Oberg, 1973).

2. Methods

2.1. Study site

The Argonne EF consists mostly of second-growth, even-aged forest, which at study establishment in 1951 was primarily 45 years old, with some scattered older, poor quality trees (Stoeckler, 1955). The experimental forest is located in Forest County, Wisconsin, with the study site being considered well-suited for northern hardwoods and having a site index of 19–21 m base age 50 (Strong et al., 1995). The *Acer/Osmorhiza-Caulophylum* habitat type and Argonne-Sarwet sandy loams with 1–6% slopes occupy most of the site (Kotar et al., 2002; USDA Natural Resources Cons. Serv.). In 1951, prior to study treatment, stand density averaged just over 21 m^2 ha^{-1} basal area in trees >11.4 cm diameter (dbh), with sugar maple accounting for 57% of that basal area, basswood 10%, hemlock (*Tsuga canadensis* L.) 9%, yellow birch 8%, white ash 6%, plus the occasional red maple (*Acer rubrum* L.), American elm (*Ulmus*

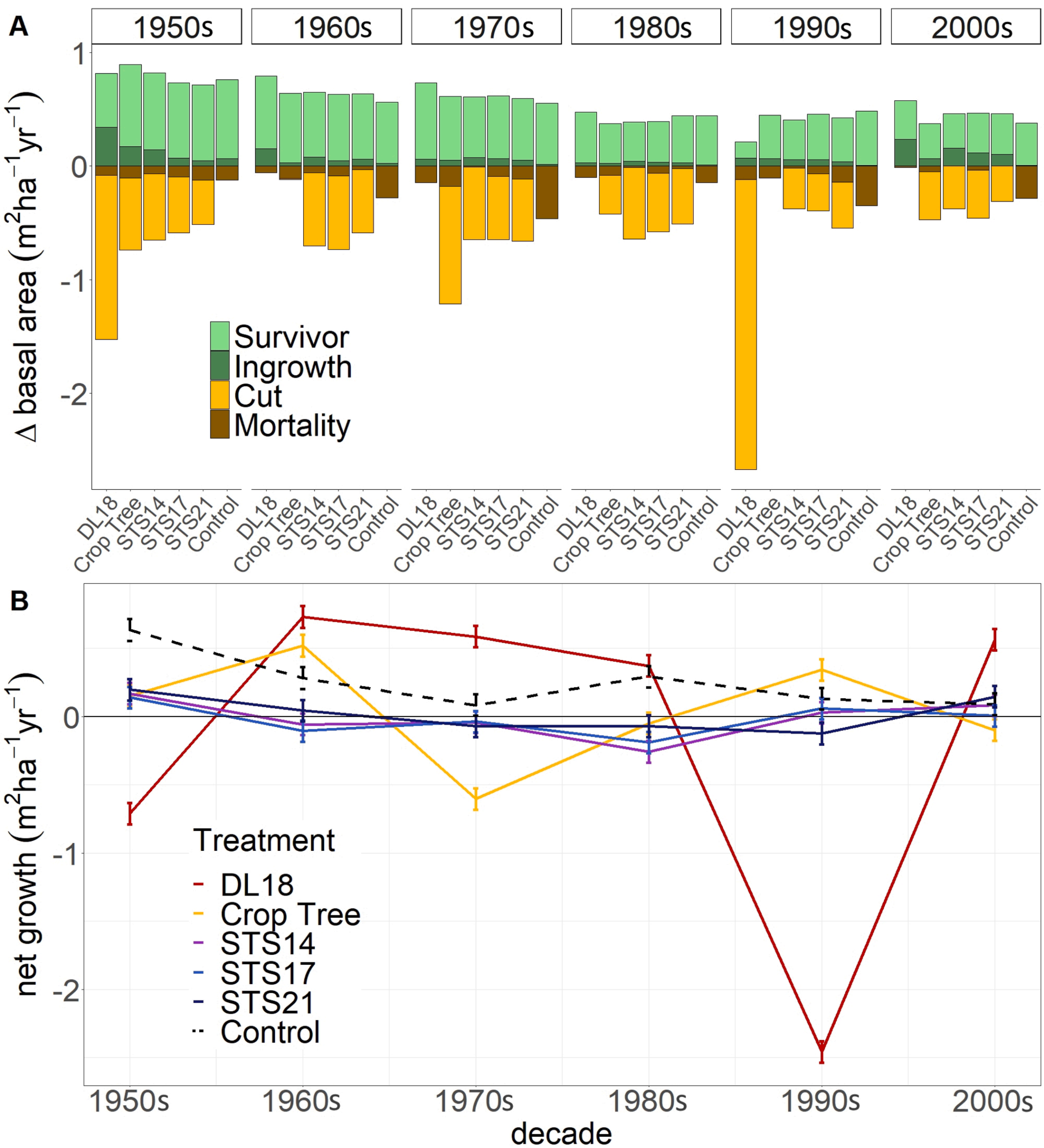

Fig. 3. Components of growth in each decade in terms of annual basal area for each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. (A) Average mortality (±0.044 m^2 $ha^{-1}yr^{-1}$), removals (±0.088 m^2 $ha^{-1}yr^{-1}$), ingrowth (±0.018 m^2 $ha^{-1}yr^{-1}$), and survivor growth (±0.03 m^2 $ha^{-1}yr^{-1}$), n = 540. (B) Average net growth (±0.079 m^2 $ha^{-1}yr^{-1}$) which consists of survivor growth + ingrowth – removals – mortality, n = 540. Standard errors given above in parentheses are from the balanced AR1 model and thus are equal across treatments and time. See section 2.2 for treatment code descriptions.

americana L.), paper birch (*Betula papyifera* Marsh.), black ash (*Fraxinus nigra* Marsh.), black cherry (*Prunus serotina* Ehrh.), aspen (*Populus* spp.), and ironwood (*Ostrya virginiana* Mill.) individuals making up the remainder (Erdmann and Oberg, 1973).

The study site composition as described above has shifted with treatments over time (see supplementary material). All treatments were sugar maple-dominated at pre-harvest in 1951. Overstory sugar maple abundance increased from 1951 to 2011 in all treatments except for the diameter-limit cut and medium selection treatment. The greatest increases were seen in the crop tree and light selection treatments. Shannon’s diversity index (H′) decreased in all treatments except for the crop tree and diameter-limit treatment, with the greatest decrease in the control.

2.2. Long-term study design

The Cutting Methods Study was established in 1951 at the Argonne Experimental Forest. The study employs a randomized complete block design, with blocks comprising three relatively uniform 16.2-ha stands. Blocks 1, 2, and 3 are located at approximately 45°44′37.6836″N, 88°59′19.4064″W, 45°44′54.96″N, 88°58′7.464″W, and 45°45′36.1908″N, 88°57′59.7888″W, respectively. Treatments were randomly assigned to 1.01 ha units within each block. The treatments consisted of nine different silvicultural treatments, including a control.

Table 3
Average annual mortality (±0.011 m^2 $ha^{-1}yr^{-1}$), ingrowth (±0.006 m^2 $ha^{-1}yr^{-1}$, into the smallest measured size class), and removals (±0.033 m^2 $ha^{-1}yr^{-1}$), for the entire study period in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. Within each column values with the same letter are not significantly different, $p < 0.05$, n = 15. See Section 2.2 for treatment code descriptions.

Treatment	Mortality	Ingrowth	Cut
DL18	0.078 *ab*	0.132 *a*	0.634 *b*
Crop tree	0.100 *b*	0.065 *bc*	0.410 *a*
STS14	0.026 *a*	0.093 *b*	0.563 *ab*
STS17	0.068 *ab*	0.065 *bc*	0.511 *ab*
STS21	0.072 *ab*	0.056 *c*	0.473 *ab*
Control	0.263 *c*	0.020 *d*	–

Because some of the treatments were not maintained, six treatments are used this study: three variations of single-tree selection, an 18-centimeter diameter-limit cut, a crop tree release, and a control. Single-tree selection treatments tested three levels of residual basal area, 21, 17, and 14 m^2 ha^{-1}. All three selection treatments were applied on a 10-year cycle with entries during the winters of 1952, 1962, 1972, 1982, 1992, 2002, and 2012. The 14 m^2 ha^{-1} single-tree selection (STS14), or heavy selection, treatment reduces trees >11.4 cm dbh to a residual basal area of 14 m^2 ha^{-1} with a goal of a size class distribution with a *q*-value of 1.3, maximum dbh 61 cm, and the 17 m^2 ha^{-1} single-tree selection (STS17), or medium selection, and 21 m^2 ha^{-1} single-tree selection (STS21), or light selection, treatments similarly reduce to residual basal areas of 17 and 21 m^2 ha^{-1}, respectively. Trees were selected for harvest to remove high risk, cull, and trees in maximum diameter or overstocked size classes and to release crop trees. In the crop tree release treatment, 25–50 selected trees in the entire 1.01 ha treatment area were selected based on potential for high quality and then were released to grow by removing adjacent competing trees (Stoeckler, 1955). Crop tree release residual basal area was 14 m^2 ha^{-1} in 1952, 17 m^2 ha^{-1} in 1972, 17 m^2 ha^{-1} in 1982, 19 m^2 ha^{-1} in 2002, and 21 m^2 ha^{-1} in 2012, with small trees left near the crop tree as trainers (Strong et al., 1995). The 18 cm diameter-limit (DL18) treatment has only been cut twice over the length of the study; in 1952 and 1992 all trees 20 cm and larger at a 30.5-cm stump height, equivalent to about 18 cm dbh, were cut, including cull trees. There was no tending in the lower size class and no residual trees greater than the diameter limit were left after harvest.

2.3. Measurements

A permanent sample plot system was established in 1951. Within each treatment unit in each block, five 0.04-ha circular sample plots were monumented and trees within the plot were individually numbered. Individual tree dbh and species were recorded, typically, at a 5-year intervals beginning in 1952 prior to the first harvest. Butt-log grade was recorded pre-harvest as an estimate of standing tree quality for all sawtimber-sized trees (>24 cm dbh) in 1972, 1982, 1992, 2002, and 2016, and for harvested trees only in 1952 and 1962, using the U.S. Forest Service tree grading system (Hanks, 1976). Cull percent and merchantable height as number of 4.88-meter logs were recorded in these same years.

2.4. Growth, mortality, and yield

Total sawtimber removals and residual standing timber volumes were estimated using Gevorkiantz and Olsen (1955) volume tables (Intl. ¼″ rule) for Lake States hardwoods. Volume conversion to cubic meters follows Winn et al. (2020). Net volume was found using percent cull as measured in the field. Butt-log tree grade was used in conjunction with whole-tree volume estimates as an estimate of volume yield by grade.

An analysis of variance (ANOVA) was completed to evaluate differences in treatment means for variation in growth, ingrowth, mortality, yield, standing volume, and grade, using R version 4.0.2 (R Core Team, 2020). Yield, ingrowth, and mortality were defined in terms of annual basal area change. The model used was for a randomized complete block design with subsampling (Kuehl, 2000), where treatment and block are fixed effects with plot nested within experimental treatment unit as a random effect. Assumptions of equal variance and normality were tested in R. When appropriate, a first order autoregressive (AR1) structure over the random effects dependency structure was used to account for autocorrelation. When the model indicated statistically significant ($p <$ 0.05) differences between treatments, post-hoc comparisons using the Tukey HSD test were made with the 'emmeans' package v1.4.7 (Lenth, 2020).

To evaluate the relationship between diameter growth and size, a diameter-increment model was created following Wykoff (1990) and Deo and Froese (2013), using R version 4.0.2 (R Core Team, 2020). The natural log of the 10-year periodic change in squared diameter was used as the response variable. Predictor variables included the fixed effects $\frac{1}{\text{dbh}}$ and treatment separately and in interaction, with plot nested within treatment unit within block as a random effect. "Dummy coding" is used to represent treatment and hence the full model provides for separate slopes and intercepts for each treatment level. The full model was compared against alternatives including common slope, common intercept, and coincidence using nested-model likelihood-ratio tests to find the most parsimonious solution. Data used were from the most recent complete 10-year harvest cycle. Assumptions about homoskedasticity and normality of residuals and random effects were evaluated using scatterplots of residuals and q-q plots.

Stocking and density were evaluated using a Gingrich-style stocking chart for northern hardwoods (Gingrich, 1971; Solomon and Hosmer, 1987). For trees 11.4 cm and above, stems per hectare was plotted against basal area to determine stocking levels in each treatment through time. Chart was developed using R version 4.0.2, with open-source code developed by SilviaTerra (R Core Team, 2020; Clough, 2019)

2.5. Quality and economics

To measure treatment performance, a specific objective was to evaluate the financial success of each treatment based on solely harvested lumber volumes and values by completing a new analysis following Rideout (1985) that includes financial analysis methodology tailored to partial cutting methods, in contrast to the cash-flow analysis incorporating residual volume values from Niese et al. (1995). Managed forest value (MFV) was used as financial criteria to evaluate treatments. No cost factors were introduced into the analysis due to the intent to compare relative, not absolute, measures of financial returns between treatments. MFV is the discounted value of the sum of an infinite series of harvests, and is intended to represent the long-term applicability of a silvicultural system. As defined by Rideout (1985), MFV requires sustainable stand structure to have been reached. Selection system silviculture treatments can require two cuttings to properly implement and reach 'sustainable stand structure' (Erickson et al., 1990; Nyland, 1998; Reed et al., 1986), so for this analysis sustainable stand structure was assumed to have been reached in 1972 after two initial harvests. Financial performance was compared between each treatment and the control using discount rates of 2, 4, 6, and 8%.

This financial analysis evaluated the lumber value return of sawlogs. Potential factory grade lumber yield estimates for harvested trees were found using equations from Hanks (1976) and incorporated differences in quality into the financial analysis. Trees were also graded following methodology in Hanks (1976), so the equations for factory grade lumber yields could be accurately applied. Lumber prices for each species and harvest year were acquired from Hardwood Market Report (D. Caldwell, personal communication, October 5, 2020) with supplemental data from Luppold et al. (2001). Accurate regional historic pricing from each year

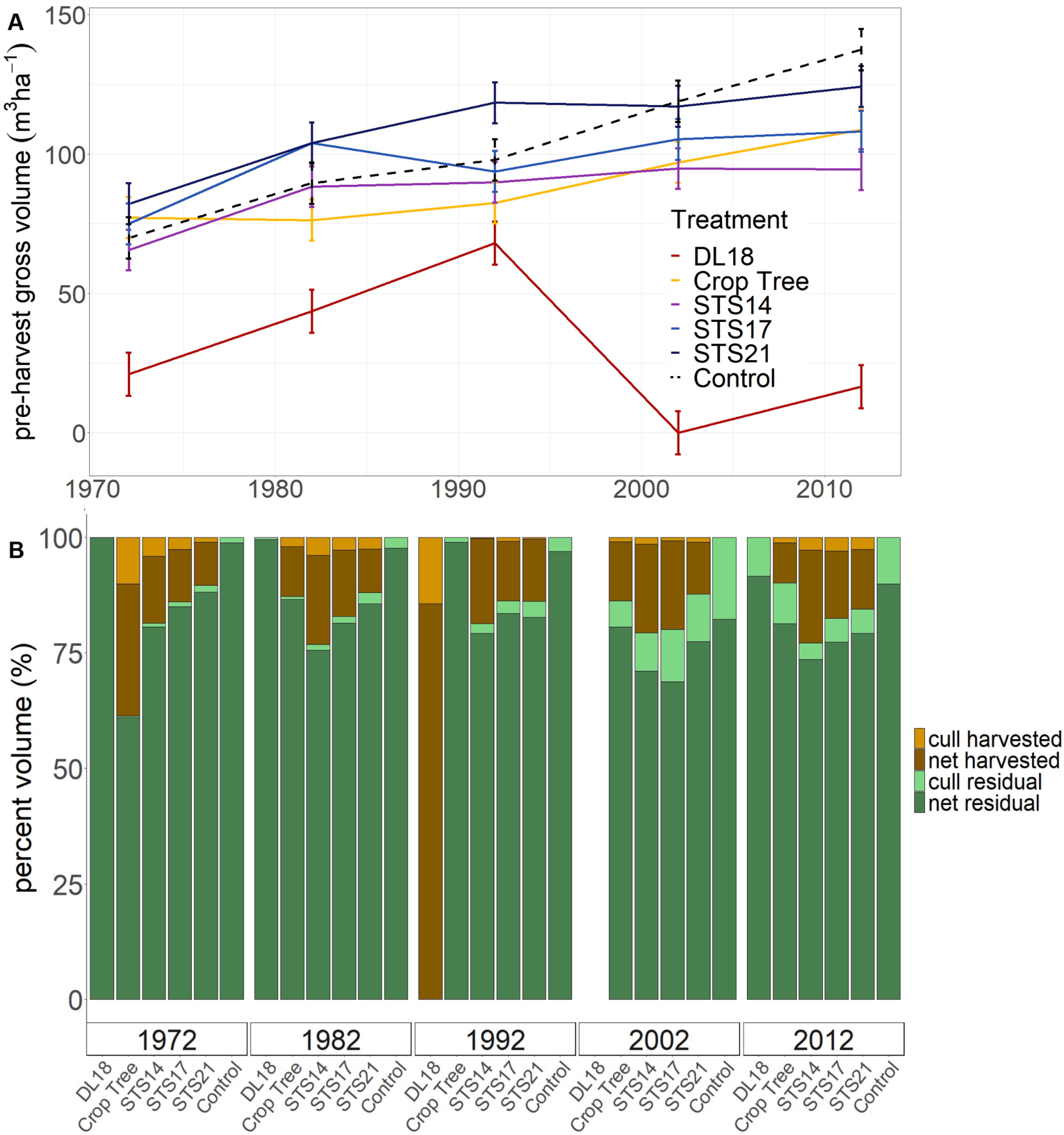

Fig. 4. (A) Average total standing sawtimber volume (±7.45 m^3ha^{-1}), n = 450 and (B) percent residual cull (±0.69%), net residual (±3.03%), harvested cull (±1.48%) and net harvested (±5.11%) volume in each year of harvest since 1972, for each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA, n = 450. Estimated using Gevorkiantz and Olsen (1955), conversion to metric following Winn et al. (2020). Standard errors given above in parentheses are from the balanced AR1 model and thus are equal across treatments and time. See Section 2.2 for treatment code descriptions.

of harvest was used, adjusted to a common 2018 basis using the producer price index for lumber and wood products (U.S. Bureau of Labor Statistics).

3. Results

3.1. Growth, mortality, and yield

For all treatments except the heavy selection (STS14) and diameter-limit cut (DL18), stocking has consistently remained above recommended minimum stocking (Fig. 1). Overall quadratic mean stand diameter has increased while there has been a slight consistent decline in basal area through time. The medium selection (STS17) holds lowest levels of stocking while staying between the A- and B-lines. The diameter-limit cut showed both overstocked, stocked, and understocked conditions over time, and the control has exhibited a consistent increase in basal area and tree size off the chart, indicating an overstocked condition.

The diameter-increment model with a common intercept, separate slopes was statistically superior to others when tested. The final (population only) model takes the form:

Table 4
For trees >24 cm dbh in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA, average merchantable height by number of 4.88-meter logs in 1972 (±0.086 logs) and 2016 (±0.112 logs). Means in a column followed by the same letter are not significantly different, $p < 0.05$, $n = 3$. See Section 2.2 for treatment code descriptions.

Treatment	1972	2016
DL18	1.29 *a*	0.72 *b*
Crop tree	1.42 *a*	1.61 *a*
STS14	1.52 *a*	1.76 *a*
STS17	1.64 *a*	1.73 *a*
STS21	1.57 *a*	1.60 *a*
Control	1.47 *a*	1.22 *ab*

Table 5
Financial analysis of each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA, with potential dry factory grade lumber yields valued at price in current 2018 dollars. Present worth is discounted to study start in 1952. See Section 2.2 for treatment code descriptions.

		STS14	STS17	STS21	Crop Tree	DL18
Periodic Return ($\$\cdot ha^{-1}$)[a]		2910	2532	1981	1744	6889
Mean Treatment Interval (years)[b]		10	10	10	13	40
MFV ($\$\cdot ha^{-1}$)[c]	2%	13,287	11,599	9046	5941	5703
	4%	6059	5289	4125	2623	1812
	6%	3679	3212	2505	1540	742
	8%	2511	2192	1709	1014	332

[a] Periodic return is averaged yearly revenue from 1972 to 2012 multiplied by number of years in treatment interval.
[b] Treatment interval is the average of the cutting cycles lengths associated with harvests between 1972 and 2012, except for the 18 cm DL where it is the interval between the only two harvests in entire study period.
[c] Calculations assume sustainable stand structure was reached in 1972.

$$\hat{y} = b_0 + (b_1 + b_2T_1 + b_3T_2 + b_4T_3 + b_5T_4 + b_6T_5)\cdot\frac{1}{DBH}$$

where $\hat{y}$ = the response and T_1 through T_5 are dummy variables that take the value 0 except: $T_1 = 1$ if treatment = control; $T_2 = 1$ if treatment = crop tree; $T_3 = 1$ if treatment = STS14; $T_4 = 1$ if treatment = STS17; and $T_5 = 1$ if treatment = STS21. Coefficients are as presented in Table 1. Note that if treatment = DL18 then all dummy variables are 0 and the slope is simply b_1.

Fifty years into the study, diameter growth in the smallest size classes was maximized in the diameter-limit cut for trees <30 cm (Fig. 2), but that same treatment did not support any growth in larger trees. Excluding the diameter-limit cut, for all size classes, incremental growth was greatest for the medium and heavy selection treatments. The greatest diameter growth rates in the selection treatments are predicted in trees around 30 cm dbh. The crop tree treatment appears to suppress growth in smaller size classes, but growth was still greater than in the control. Sixty-five years into the study, average diameter was smallest in the diameter-limit, and largest in the control (Table 2).

Ingrowth has been consistently higher in those treatments that remove more of the basal area (Fig. 3A; Table 3). The diameter-limit cut has the greatest levels of ingrowth, followed by the heavy selection. The heavy selection also tended to have low mortality through time and was significantly lower in mortality compared to other treatments in the 1970s and 1990s, as well as having overall lowest mortality (Fig. 3A; Table 3). Since the 1960s, mortality has been significantly higher in the control than other treatments. Survivor growth has decreased through time, due to increasing tree size (diameter) and simultaneous decreasing diameter growth over time. However, in the most recent decade, net growth has become positive for all treatments, with the exception of the crop-tree release declining to be about zero (Fig. 3B). The selection treatments tended to waiver just above, at, or just below zero net growth over time. Only the control has consistently had positive net growth. The crop tree and diameter-limit treatments showed high variation with significantly higher and lower net growth compared to other treatments over time. Basal area removals in all three selection treatments were not significantly different when averaged over the entire study period, with the crop tree having the lowest average total removals (Table 3). Total standing volume has increased since 1972 for all treatments except the diameter-limit (Fig. 4A), with the greatest gains in the light selection (STS21) and control and least in the crop-tree and heavy selection. Average merchantable height also increased in all treatments except for the diameter-limit and control, with no significant differences in merchantable height between selection or crop tree treatments after sixty-five years of treatment (Table 4). The diameter-limit cut is the only treatment to have a lower standing sawtimber volume in 2012 than in 1972. Percent cull volume in residual trees has increased through time, however, percent cull volume in harvested trees has decreased (Fig. 4B). By 2012, percent cull volumes in the residuals were significantly greatest in the diameter-limit, control, and crop-tree treatments and lowest in selection treatments. However, the crop-tree treatment had the lowest percent cull in harvested volumes.

3.2. Quality and economics

MFV was maximized by the heavy selection treatment at all discount rates, closely followed by the medium selection treatment (Table 5). The diameter-limit cut compares poorly under MFV, with only 30% of the value of the heavy selection at a 4% discount rate. This discrepancy only increases at higher discount rates. After the diameter-limit cut, the crop tree treatment performed poorest at all discount rates; at 4% it has an MFV value less than half of the medium selection and just 43% of the heavy selection.

From 1982 to 2002, percent harvested grade 1 volume was consistently highest in the selection treatments, joined by the crop-tree treatment in 2012 (Fig. 5). The heavy and medium selection generally had greater percent grade 1 yield than the light selection. Overall, the crop tree treatment has had the total lowest percent yield of estimated high-quality sawtimber second only to the diameter-limit cut. As the stand has aged and average diameters increased, both percent residual and harvested grade 1 volumes also increased in all treatments except the diameter-limit cut, with the greatest increases seen in the selection treatments. Excluding the diameter-limit cut and the control, the residual grade distribution in all treatments has improved since 1972 with a notable decline in percent grade 3 volumes and increase in percent grade 1. The heavy selection in particular exhibits this trend, with the lowest percent grade 3 and highest percent grade 1 residual volumes by 2012. Sixty-five years into the study, average plot grade was maximized by the heavy selection treatment, and significantly lowest in the diameter-limit cut (Table 6).

4. Discussion

Long-term studies such as this one provide a unique opportunity to evaluate the financial success and sustainability of forest management on a time scale valuable to managers of slow-growing, longer-lived forests, such as sugar-maple dominated northern hardwoods. Financial performance in particular is often a driving factor of forest management, with a continual good and sustainable performance being most desirable. These 65-year results demonstrate the ongoing performance of partial cutting methods in terms of volume, stocking, growth, and quality. Quality in particular heavily influences financial return in northern hardwoods ((Reed et al., 1987); Sendak et al., 2000). Grade improvements result in the greatest increases in monetary value, more so than growth in diameter or height (Godman and Mendel 1978). The treatments which continually produce high-quality sawtimber while also increasing quality of residuals were thus expected to perform best

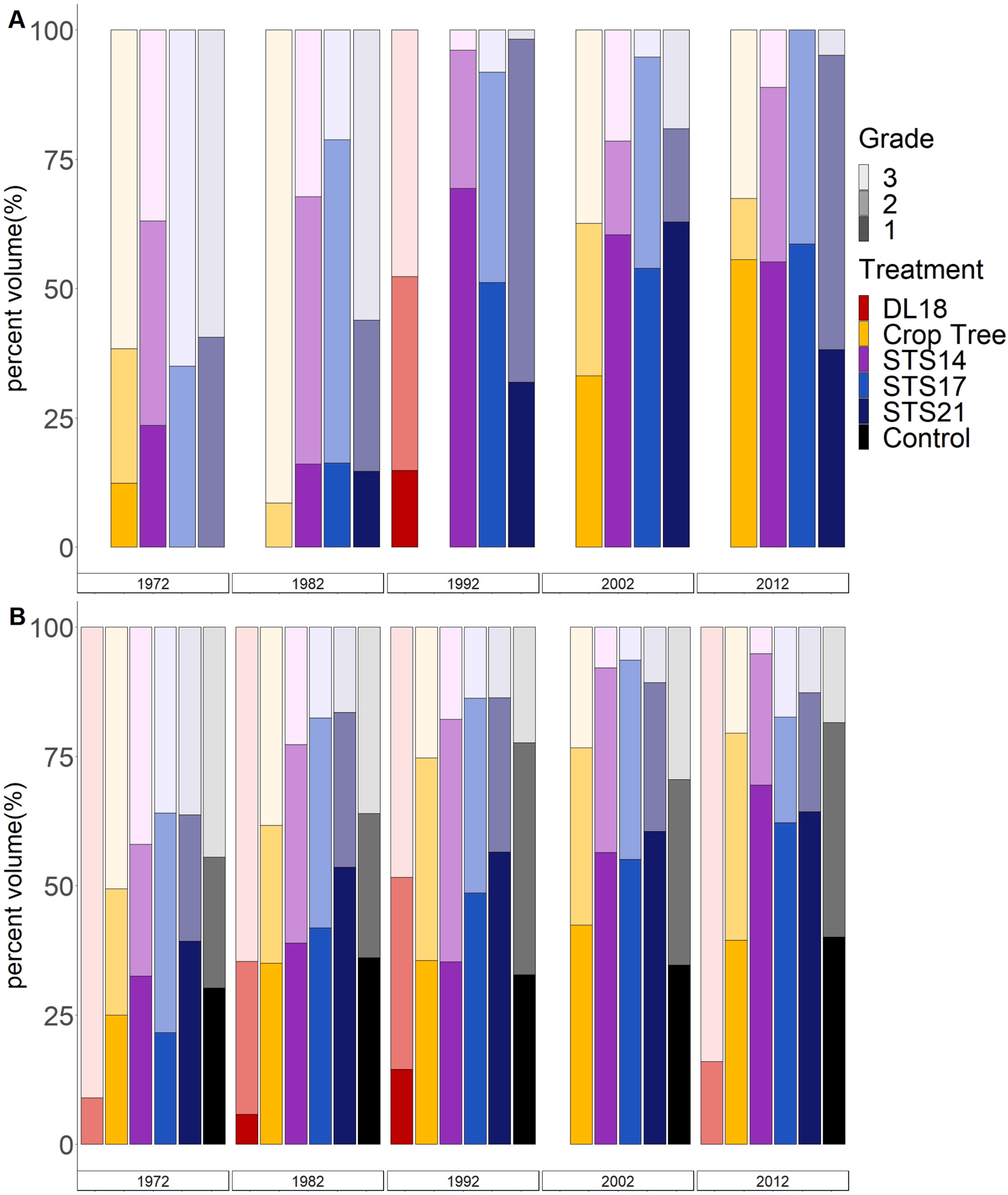

Fig. 5. For each treatment in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. (A) Average percent of estimated harvested volumes by grades 1 (±7.4%), 2 (±7.1%) and 3(±7.3%), n = 375. (B) Average percent of estimated residual volumes by grades 1 (±7.3%), 2 (±6.1%) and 3 (±5.7%), n = 450. Volumes estimated using Gevorkiantz and Olsen (1955). Butt-log tree grade following Hanks (1976). Standard errors given above in parentheses are from the balanced AR1 model and thus are equal across treatments and time. See Section 2.2 for treatment code descriptions.

financially. Single-tree selection is known to increase quality of both harvested and residual trees (Brown et al., 2018; Leak and Sendak, 2002), and lower residual basal areas have been seen to produce higher quality trees (Erickson et al., 1990). Thinning is known to positively affect residual timber size and quality, and in long-term studies has increased species diversity, regeneration, and structural development ((Curtis et al., 1997); Zeide, 2001). Previous long-term studies at the Argonne EF (Niese et al., 1995; Strong et al., 1995) found that a medium selection treatment to 17 m^2 ha^{-1} residual basal area had the greatest increase in quality over 40 years, but the heavy selection treatment to

Table 6
For trees >24 cm dbh, average plot tree grades in 1972 (±0.144 cm) and 2016 (±0.169 cm) in the Cutting Methods Study in a northern hardwood forest, Argonne Experimental Forest, WI USA. Grade scale from Hanks (1976), sawtimber grades 1–3 with below grade assigned a value of 4. Means in a column followed by the same letter are not significantly different, $p < 0.05$, $n = 3$. See section 2.2 for treatment code descriptions.

Treatment	1972	2016
DL18	3.33 *b*	3.20 *c*
Crop tree	2.82 *ab*	2.13 *ab*
STS14	2.54 *a*	1.69 *a*
STS17	2.62 *a*	1.89 *ab*
STS21	2.54 *a*	2.14 *ab*
Control	3.04 *ab*	2.61 *bc*

14 m^2 ha^{-1} residual basal area had the highest economic returns. The additional two decades of treatment captured in this analysis have resulted in a confluence of quality and economic success; the heavy selection treatment now has the greatest economic returns as well as greatest percentages of residual high quality sawtimber volumes.

Since 1972, managed forest value and the total volume percentages of harvested grade 1 volume have been maximized by the heavy selection treatment. Managed forest value (MFV) is a good indication of continuous repeatable return; since a key feature of selection silviculture is continuous stocking, a measurement like MFV that assesses return under repeated harvest entries of the same treatment is very appealing when evaluating selection and other partial cutting treatments. The financial performance of the heavy and medium selection under MFV at all discount rates thus indicates success on an ongoing basis, as well as substantial future financial returns. This sustainable financial success is also reflected in the consistency of the net growth in the selection treatments. The crop tree has had a less consistent net growth through time, and despite having increased quality in similar ways to the selection treatments also has a much lower managed forest value at less than half of the heavy selection. However, the low-threshold 18 cm diameter-limit cut performs comparably worse in the long-term with both inconsistent returns and poor overall quality.

The heavy and medium selection treatments have financially outperformed the crop tree treatment and light selection in part because diameter growth greatly affects tree grade improvement (Dey et al., 2017; Webster et al., 2009). Lower densities in northern hardwood forests are known to improve diameter growth (Eyre and Zillgitt, 1953), and the results from this study show consistent increases in individual-tree diameter growth as residual basal area decreases (Fig. 2). As trees become larger they surpass more of the threshold requirements for grade 1 and grade 2 standards (Hanks, 1976), so it follows that both diameter growth and grade increases are more rapid in the heavy and medium selection treatments. Growth in diameter classes directly below grade 1 thresholds (around 40 cm dbh for northern hardwoods) in particular results in a sharp increase in value as those thresholds are surpassed (Hanks, 1976; Reed and Mroz, 1997). In contrast, despite high individual-tree growth rates the DL18 does poorly financially because trees are removed before they can grow large enough to meet the thresholds for the most valuable grades. This phenomena is also shown in how the crop tree treatment performs poorly in the financial analysis despite producing high volumes of grade 1 sawtimber in the last two harvest cycles; diameter growth is suppressed in the 30 – 40 cm dbh size classes where these dramatic increases in value occur. The crop tree treatment is meant to improve quality, but is inconsistent in quality of harvested volumes. Residual grade 1 percentages are also not as large as the selection treatments, and are actually very comparable to the control through time. Greater and more consistent removals might help crop tree financial performance into the future.

However, there is a limit to the gains in quality afforded through diameter growth; the rate of value gains declines in larger trees (Godman and Mendel, 1978), and larger trees present a higher chance for damage, decay, or defect (Dey et al., 2017; Erickson et al., 1992; Luley et al., 2009). Quality as assigned by grade is also size dependent, so not all diameter growth is equally comparable; faster growth rates of trees cut prior to reaching grade 1 is not equal to volume growth of trees cut immediately after achieving an assignation to the highest grade. For these reasons maturity in northern hardwoods is a result of economics, not age (Arbogast, 1957). In the Lake States there is a particular issue with increasing dark heart as sugar maple trees age (Erickson et al., 1992), which has been shown to be more prevalent in trees with slower growth rates and larger diameters (Kaminski et al., 2019). The greatest gains in value are often seen in trees just entering the sawlog class, and as previously mentioned, those in the 31, 36, and 41-cm diameter classes (Power and Havreljuk, 2018; Reed and Mroz, 1997; Smith and Miller, 1987). So once a high-quality tree surpasses these thresholds, the optimal time to harvest is likely before there is an opportunity to decrease in value. The STS14 and STS17 have produced greater volumes of high-quality sawtimber by removing more of the trees in these size classes, and by holding on to fewer in the largest classes. The crop tree perhaps retains too many large trees, along with the STS21. The diameter-limit treatment has too low a threshold to regularly produce high quality trees; a larger threshold diameter and more frequent re-entry would likely improve the MFV of the diameter limit cut. Differences in grading rules by species may affect these conclusions, although in this region differences are minimal at best with only a 2.5 cm difference in the grade 1 diameter threshold for basswood and ash, which make up under 25% of the stand composition.

Quality directly drives financial performance, but repeatable returns and the sustainability of a management method are directly affected by growth metrics such as ingrowth and mortality. By definition silvicultural systems plan for regeneration, and so the practice of applying an uneven-aged single-tree selection silvicultural system to an even-aged forest may need to be re-evaluated in the context of a lack of regular ingrowth into smaller size classes that is present in the selection systems evaluated here. Some combination of treatments might be superior; the highest ingrowth levels are seen in the DL18, which is reflected in the positive net growth seen in non-harvest decades, while the heavy selection treatment lowers mortality. Ingrowth and mortality as components of growth do affect the value of the residual stand, however, economic return is not realized until volume is removed from a stand and sold. Not only were there greater overall volume removals as a result of the heavy selection treatment, but more grade 1 and better volume was removed since 1972, which significantly impacts the financial success of any given treatment. The crop tree treatment may have improved quality of trees, but unless those trees are removed, financial success will not be impacted. Crop tree release reduced cull in the removed volume, but has not produced enough yield to compete with heavy and medium selection treatments (Fig. 4). Greater volume removals in the STS14 and STS17 also boosted the diameter growth rate in the residuals so that more high quality sawtimber could be produced over time.

Relatively larger removal of the basal area in a stand can also result in greater ingrowth and helps mitigate dominance of shade-tolerant trees (Curzon et al., 2017). There have been concerns about trends towards sugar-maple monoculture under traditional single-tree selection as applied in northern hardwoods (Angers et al., 2005; Neuendorff et al., 2007), and so it is important for future management to recognize that reducing basal area to a greater degree may offset this trend. Including aspects of larger scale disturbance in selection methods could help preserve diversity (Angers et al., 2005), and indeed lower basal areas in selection methods have been associated with higher overstory diversity (Niese and Strong, 1992; Strong et al., 1995). Selection management also increases structural complexity in second-growth hardwoods (Crow et al., 2002), and diversification of forest structure by acquiring many different size classes and successional types is important for many reasons including forest health, wildlife, and continual productivity (Wiedenbeck, 2020). Varying stand structure can also help increase overstory diversity (Hanson and Lorimer, 2007), which is important in this context because uneven-aged management increases the dominance of shade-tolerant trees in Great Lakes northern hardwoods (Crow et al., 2002).

Overall, treatments that remove more of the basal area result in a better return on investment while providing ecological and sustainability benefits as well. In selection treatments, lower residual basal areas have been found to result in greater residual growth and lower mortality (Forget et al., 2007). Schuler and McGill (2007) found that basal areas of about 12.6 m^2 ha^{-1} may be optimal for increasing periodic sawtimber yield in hardwoods. The STS14 has had consistently the lowest mortality, high diameter growth in all size classes, and greatest grade 1 and total volumes harvested. All of these factors contribute to higher economic returns. Moreover, there is an opportunity cost inherent in retaining older trees. Treatments such as the STS21 that retain relatively high volume, especially in larger trees, are not capitalizing on the value of high-quality trees. The ratio of growth to removals in northern hardwood forests has been the highest in the country for many decades, indicating that increased sawtimber removals can be implemented and may benefit forests (Wiedenbeck, 2020).

Extremely high removals, particularly severe diameter-limit cuts, are clearly shown to be unsuccessful in producing high-quality trees or consistent yield and financial returns. The DL18 ranked last in all assessed quality and growth metrics. Harsh diameter-limit cuts carry other concerns for forest managers as well, such as potential dysgenic effects that can accumulate through time (Buongiorno et al., 2000). However, only one threshold diameter limit was tested here; recently published results from a long-term study in northern hardwoods that compared a range of limits has shown that medium-intensity cuts (e.g., a 41 cm limit) can prove superior even to single-tree selection on financial, yield, and regeneration criteria (Draper and Froese, 2021). Medium-intensity diameter-limit cuts with improvement are suggested by Buongiorno et al (2000) and Smith and Miller (1987), and financial-maturity diameter-limit treatments have been used as a variant on the selection system to combine silvicultural considerations with financial concerns (Schuler and McGill, 2007; Trimble et al., 1974). Diameter-limit cuts below 20 cm, such as the one evaluated here, have long been known to perform poorly under financial evaluation, with few if any redeeming silvicultural, environmental, or financial attributes (Draper and Froese, 2021; Hough, 1954).

5. Conclusion

Return on investment plus continual and sustainable success are strong incentives for any management method, and so treatments such as the STS14 and STS17 that encourage ingrowth, lower mortality, improve quality, and perform well financially could be considered as potential alternatives to high residual basal area traditional single-tree selection as it is currently prescribed in northern hardwoods. Such alternatives are being increasingly considered as concerns about the sustainability of the selection system become more prevalent (Campione et al., 2012; Danyagri et al., 2019; Henry et al., 2021; Kern et al., 2014; Matonis et al., 2011). The long-term nature of this study lends confidence to these results, and the study is ongoing with the potential for future evaluation giving further support. Understanding that sustainable forest management with alternative silvicultural methods includes a balance between managing for financial returns, long-term sustainability, and ecological concerns is necessary for the successful management of northern hardwood forests into the future.

CRediT authorship contribution statement

Maeve C. Draper: Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Christel C. Kern:** Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **Robert E. Froese:** Methodology, Formal analysis, Resources, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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