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silviculture

Short- and Long-Term Results of Alternative Silviculture in Peatland Black Spruce in Minnesota, USA

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Across the boreal forest in North America, the black spruce (*Picea mariana*) cover type is ecologically and economically important, occupying roughly 10 percent of Minnesota's, USA 17.4 million acres (7.0 million hectares) of forestland. Traditionally managed through clearcut regeneration harvests, alternative silvicultural systems are being increasingly used in Canada. Here, we examine the 10- and 57-year effects of six silvicultural treatments (clearcut strips, clearcut patches, thinning, group selection, single-tree selection, shelterwood) on stand structure and dynamics in lowland black spruce. Treatments were installed in 1948 in northern Minnesota, and remeasured and re-treated 10 years later. A subset of the clearcut strips, clearcut patches, and shelterwood treatments were remeasured in 2017. After 10 years, diameter growth of residual stems varied by treatment, with the shelterwood experiencing the greatest growth, and basal area increased in all but the shelterwood treatment. Over the long term, the shelterwood exhibited larger diameters and heights and greater crown ratios, basal area, structural complexity, and compositional diversity than the clearcuts. Our results suggest that managers may consider using a shelterwood instead of traditional large clearcuts to achieve increased structural and compositional diversity, particularly when eastern spruce dwarf mistletoe (*Arceuthobium pusillum*) does not necessitate a traditional clearcut.

Study Implications: This research suggests that alternatives to traditional clearcutting of black spruce stands in the United States Lake States have merit and may be used by managers to achieve stands that supply additional options in the future. In stands of older ages where advance regeneration is already present, a shelterwood treatment provides a means to achieving sufficient regeneration without the use of aerial seeding while also resulting in future stands that have larger-diameter trees, greater basal area, increased structural complexity and compositional diversity, and potentially a shortened rotation age. Additionally, a shelterwood increases diameter growth on residuals to make overstory removal more economically feasible. Consideration should be given to the amount of residual growing space to reduce mortality because of wind events over the short-term, possibly by aggregating residuals.

Keywords: quantitative silviculture, forest structure, long-term research, experimental forest, ordination

Black spruce (*Picea mariana* [Miller] B.S.P.) is the most abundant tree species across North American boreal forests and is important both economically and ecologically (Viereck and Johnston 1990, Groot 1995). Black spruce is an important commercial species in the Lake States region (Michigan, Minnesota, Wisconsin) of the United States (Viereck and Johnston 1990). In Minnesota, black spruce comprises 1.6 million ac (648,000 hectares) of the 17.4 million forested ac (7.04 million hectares) (Miles 2017) and is the second-most-harvested pulpwood species by volume (Minnesota Department of Natural Resources 2017). Black spruce forest types constitute important habitat for many wildlife species, including snowshoe hare (*Lepus americanus* [Erxleben]), spruce grouse (*Falcipennis canadensis* [Linnaeus]), American marten (*Martes americana* [Turton]), salamanders (Salamandridae family),

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cavity-nesting birds, and other small mammals (Cimon-Morin et al. 2010).

Natural-resource managers traditionally have regenerated black spruce stands using even-aged systems, particularly traditional clearcutting methods (Viereck and Johnston 1990, Groot 1995, Youngblood and Titus 1996). Clearcutting is often followed by aerial seeding to facilitate artificial regeneration (Weetman 1975, Johnston 1977b, Groot 2002), which occasionally follows either prescribed fire or scarification to improve seed bed conditions (Johnston 1977b, Kolabinski 1991). Prescribed fire is used less frequently because of costs and logistical difficulties (Groot 1995). Strip and patch clearcuts have been used as alternatives to the traditional clearcut system because the narrow cuts facilitate natural seeding within the seed dispersal distance of black spruce, which is up to 260 feet (79 meters; Johnston 1977b, Viereck and Johnston 1990, Groot 1995).

In Eastern Canada, the use of alternative even-aged silvicultural systems to clearcutting has been explored, especially systems that take advantage of advance regeneration (Groot and Hökkä 2011). Shelterwood systems have been suggested where advance regeneration is already present (Groot 2002, Groot et al. 2005). Groot et al. (2005) note that in older stands where advance regeneration exists, developments in logging equipment have made feasible practices that can protect regeneration during harvesting such as that termed "Careful Logging Around Advance Growth" (CLAAG) in Ontario (known as "Coupe avec Protection de la Regeneration et des Sols" or CPRS in Quebec). The objective of CLAAG is to remove merchantable trees (greater than 5 in. [9 cm] dbh) and results in a forest structure that is fairly uniform. Ruel et al. (2013) have shown that CLAAG reduces structural features that are common in uneven-aged, irregular forests, particularly in comparison with selection methods.

Another form of retaining advance regeneration is "Harvesting with Advance Regeneration Present" (HARP) in Ontario (known as "Coupe avec Protection des Petites Tiges Marchandes" or CPPTM in Quebec). HARP aims to cut all trees greater than 5.5 in. (14 cm) dbh while protecting advance regeneration. The resulting structure is less even in size than CLAAG, and with mixed results in terms of structural components typical of uneven-aged stands. Deans et al. (2003) found that the HARP system aided the retention and redevelopment of structural features common in unmanaged lowland black spruce forests such as older trees, larger diameters and heights, and a diameter distribution that followed a reverse-J curve. Ruel et al. (2013) showed strong decreases in Shannon's diversity index when compared to using selection methods. Finally, thinning black spruce as an intermediate treatment has been shown to increase net merchantable volume by up to 33 percent over unthinned stands after 15 years (Soucy et al. 2012) and improve post-treatment radial growth by 20–100 percent over pretreatment growth (Vincent et al. 2009).

Uneven-aged silvicultural systems in black spruce have been recommended under certain conditions. In Minnesota, uneven-aged methods were explored in the mid- to late-20th century. Group or individual tree-selection methods have been suggested in stands on poor sites where layering is common (Heinselman 1959, Johnston and Smith 1983). Although partial cutting has increased diameter growth in both even- and uneven-aged stands, diameter growth is inconsistent in uneven-aged stands because of the variability in stand density (Pamerleau-Couture et al. 2015, Anderson et al. 2018). Partial selection cuts have resulted in slow understory growth of black spruce in Minnesota (Heinselman 1959), and traditional clearcuts are still seen as more economically efficient operations (Groot 2002, Ruel et al. 2013).

Despite previous studies assessing alternative silvicultural systems in Canada and the Lake States, there is limited understanding of the short- and long-term effects of a variety of silvicultural treatments on stand dynamics in lowland black spruce (Groot et al. 2005). Additionally, interpretations of the effects and suitability of alternative silvicultural treatments in black spruce in relation to disturbance events and across a variety of stand ages and conditions are needed.

This study aims to help fill the gap in understanding the effects and applicability of alternative silvicultural systems in lowland black spruce stands in the Lake States with a variety of stand conditions. The specific objectives of this study are to (1) quantify the effects of six alternative silvicultural treatments on individual tree diameter growth, stand basal area increment, and individual tree mortality 10 years after the initial treatment, and (2) quantify the effects of three of those same silvicultural treatments 50 years after the final treatment on the density, structural complexity (Gini coefficient, uncompacted crown ratio, standing and downed dead wood), and stand composition (Shannon's diversity, understory species richness).

Methods

Study Area

The "Compartment Study" (USDA Forest Service 1948) was initiated by the USDA Forest Service Lakes States Forest Experiment Station and took place on the Big Falls Experimental Forest in northern Minnesota, USA near Big Falls (48°21′N, 93°46′W, 1220 ft [372 m] above sea level). The climate is continental with short, warm summers and long, cold winters. Maximum summer temperatures can exceed 90° F (32° C) with high humidity (80 percent), and minimum winter temperatures can reach –31° F (–35° C). Precipitation ranges from 20 to 25 in. (500 to 640 mm), with average snowfall around 60 in. (152 cm) (Adams et al. 2004). The study occurs in the lowland black spruce cover type, black spruce group (12) (Eyre 1980), and the Northern Rich Spruce Swamp Native Plant Community type (FPn71) (Aaeseng et al. 2003). In Minnesota, this cover type is found almost exclusively on wet sites in organic, peatland soils that begin as even-aged and transition to uneven-aged in the absence of major disturbances. Stands are nearly purely black spruce, but also contain tamarack (*Larix laricina* [Du Roi] K. Koch), balsam fir (*Abies balsamea* [L.] P. Mill.), and paper birch (*Betula papyrifera* Marshall).

Compartment Study

Six silvicultural treatments and a control were established in 1948. Treatments included three even-aged methods, two uneven-aged methods, and an intermediate treatment (Table 1). The three even-aged methods were clearcut strips and clearcut patches (3–4 entries over 16 years to harvest the stand; strips up to 66 feet [20 m] wide, patches up to 132 feet [40 m] wide) and a shelterwood (leaving evenly spaced, wind-firm trees; shelterwood cut to approximately 50 $ft^2\ ac^{-1}$ [11.5 $m^2\ ha^{-1}$]; overstory removed 10–11 years later). The two uneven-aged methods were group and tree selection (individual trees or groups of four to eight trees cut with the goal to maintain a well-stocked stand). The intermediate treatment

Table 1. Silvicultural treatment type and description, measurement, and treatment dates in black spruce stands on the Big Falls Experimental Forest in northern Minnesota, USA.

Type	Treatment	Description	Measurement dates				Treatment dates			
Even-aged	Clearcut strips	North–south cuts (two to three per compartment); 66–132 ft (20–40 m) wide beginning from east side; 3–4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Clearcut patches	Patches of any shape, 0.25–0.50 ac (0.10 to 0.20 hectares) in size; 3–4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Shelterwood	Cut from below to ~50 $ft^2\ ac^{-1}$ (11.5 $m^2\ ha^{-1}$) leaving strong and vigorous trees; residual stand removed ~10 years later, avoiding damage to understory	1951	1956	1960	2017	1951	1961	–	–
Uneven-aged	Group selection	Groups of 4–8 trees cut, openings not larger than 33 ft (10 m) in diameter; develop uneven-aged conditions through variable cutting cycles; entries depending on conditions	1951	1956	1960	–	1951	1961	–	–
	Tree selection	Individual trees of all sizes cut to develop uneven-aged conditions through variable cutting cycles	1951	1956	1960	–	1951	1961	–	–
Intermediate	Light thinning	Maintain full canopy while capturing mortality; variable cutting cycle, goal of every 8–10 years; regenerate with best method when stand can no longer be thinned	1951	1956	1960	–	1951	–	–	–

was a thinning to capture mortality and provide growing space for residual trees.

Each of the six treatments and the control were replicated three times, totaling 21 compartments. Compartments ranged in size from 5.8 to 9.5 ac (2.3 to 3.8 hectares). Depending upon the treatment, compartments contained eight to 16 permanent 0.1-ac (0.405-ha) plots that were monumented with plot center posts. At the study's establishment, treatments were between 99 and 137 years of age. Most compartments contained only a single stand of one condition, whereas others contained two to three stands of different ages and site index values.

A series of treatments and measurements were carried out between 1948 and 1967 (Table 1). Measurements were taken prior to the initial treatments in all compartments between 1948 and 1950. Two additional measurements were taken—one about 5 years after the initial treatment, and another about 10 years after the initial treatment and just prior to a second treatment around 1960. All compartments were treated both initially in 1948 and at 10 years except the control and the thinning, which only received the initial treatment. Harvests in clearcut strips and patches were completed over two additional treatments after 1960, resulting in total harvest in those treatments. Both the measurements and treatments were carried out over two seasons because of the size of compartments and number of replicates (Table 1).

Individual tree variables were measured on overstory trees 3.6 in. (9.14 cm) and greater in diameter at breast height (4.5 ft [1.3 m] above the ground; dbh). Variables measured on every tree were species, dbh, crown class, crown vigor, and form and health descriptions. On a subset of two to four trees per plot, total height was recorded, and approximate age was recorded via an increment core at breast height. Plot-level variables assigned were site index and age. Individual trees within each plot were stem-mapped and numbered such that repeated measurements were recorded initially and at 10 years for each tree. On dead trees, cause or mortality was recorded in the field if it could be deciphered. Otherwise, it was counted as unknown.

2017 Remeasurement

After the study was closed in 1977 (Johnston 1977a), regeneration harvests unassociated with the study occurred in 60 percent or more of the compartments by 2017. In 2017, two of the three original compartments in the shelterwood, clearcut strips, and clearcut patches, treatments remained wholly or partially unharvested. All remaining plots were remeasured in summer 2017. A large proportion of plot center posts were relocated from the original study. Where plot centers were not recovered, original stand maps that denoted the distance between plots were used to re-establish missing plot centers. Although the re-established plots may not contain the original plot area in all cases, we are confident that they represent the same stand conditions. Combined across the two compartments remaining in each treatment, the shelterwood treatment had 17 of the initial 30 plots intact, the clearcut strips treatment had 29 of 48, and the clearcut patches treatment had 32 of 43.

Variables remeasured were largely the same as the initial measurements. Total height and height to live crown were measured on a subset of three dominant or codominant trees per plot. Additionally, one 0.01-ac (0.00404686-ha) plot nested within the larger plot was measured to assess regeneration. All stems of tree species less than 3.6 in. dbh (9.144 cm) were tallied by species.

Standing deadwood was assessed by measuring the dbh of all standing dead trees in the plot greater than 3.6 in. dbh. Coarse woody debris (CWD) was measured following the approach outlined by the USDA Forest Service for the Forest Inventory and Analysis program (USDA Forest Service 2011). On every plot, one transect at a random azimuth intersecting the plot center was run across the entire plot diameter (74.4 feet). The diameter of deadwood on the forest floor that intersected the transect was measured if it met criteria for a predefined decay class. A decay class was assigned for each piece ranging from 1 to 5 depending on its decay condition, where:

$$DC = decay\quad class \begin{cases} 1 = sound;\ no\quad decay \\ 2 = sound;\ sapwood\quad beginning\quad to\quad decay \\ 3 = sound\quad heartwood;\ decayed\quad sapwood \\ 4 = decayed\quad heartwood \\ 5 = no\quad structure;\ soft\quad and\quad powdery \end{cases}.$$

For decay classes 1–4, the diameter at the intersection and length from its large end to a minimum diameter of 3.0 in. (7.6 cm) were recorded if its diameter at the point of intersection was 3.0 in. or greater, and its length was at least 3.0 feet (0.914 m). A piece in decay class 5 was measured similarly to the above classes if its diameter at the point of intersection was at least 5.0 in. (12.7 cm).

Dead trees and tall stumps that were leaning greater than 45° from vertical that met the criteria were counted as CWD and measured accordingly.

Computed Variables

Short Term

To assess the effects of all six treatment after 10 years, a number of stand-level metrics were assessed. At the 10-year remeasurement, treatments had only experienced an initial cut (Table 1). The clearcut strips, clearcut patches, group selection, and tree selection had received only one removal. The shelterwood treatment had received the initial shelterwood cut but not the overstory removal. The 10-year analysis assessed differences in individual tree diameter growth, stand basal area increment, and individual tree mortality. In the clearcut treatments and the group selection treatment, some plots were harvested either completely or partially depending on the boundaries of the clearcuts in the initial 1948–50 treatment. Stand basal area increment in the clearcut treatments was only calculated for residual plots experiencing no initial treatment. Mortality was calculated by plot as a percentage by dividing the total number of dead trees by the total number of total standing trees in the 10-year measurement that were present and not harvested in the initial measurement.

Long Term

Density

For the long-term analysis, two common measures of stand density were assessed to determine differences among treatments: trees per acre and basal area per acre.

Structural Complexity

Stand structure was evaluated using several common stand-level measurements and additional metrics to quantify structural complexity and heterogeneity in the various treatments. At the individual tree level, mean dbh, total height, and uncompacted live crown ratio (UCR) were assessed to quantify treatment differences. UCR is defined as

$$\mathrm{UCR} = \frac{\mathrm{Ht} - \mathrm{HCB}}{\mathrm{Ht}}$$

where Ht is the total height, and HCB is the height to the base of the crown. A higher ratio corresponds to a higher proportion of the tree being occupied by branches with live foliage, which equates to a greater vertical structure.

Additionally, the Gini coefficient was calculated for each plot as a measure of tree size inequality using the form suggested by D'Amato et al. (2011) as:

$$\mathrm{Gini}_{\mathrm{dbh}} = \frac{\sum_{i=1}^{n} (2i - n - 1)\, x}{n^2 \mu}$$

where $\mathrm{Gini}_{\mathrm{dbh}}$ is the Gini coefficient of a plot, i is a tree number assigned from a tree list ordered by ascending dbh, n is the number of trees in a plot, x is the dbh of tree i, and μ is the mean dbh of the plot. Values for a plot range from 0 to 1 where 0 represents stands that have a perfect size equality where all individuals are equal, and 1 represents stands with a maximum level of size inequality (Weiner and Solbrig 1984).

Deadwood was the final component of stand structure assessed for differences based on treatment. Standing dead basal area and trees per acre were evaluated to assess treatment differences in standing deadwood structure. CWD on the forest floor was also compared between treatments. To determine volume of CWD, end-point diameters and total length were first estimated by equation provided by Woodall et al. (2008), and then volume was calculated using the formulas suggested by Woodall and Monleon (2008).

Compositional Complexity

Attributes of stand composition were assessed to quantify the abundance and diversity of tree species within stands. Shannon's diversity index (Shannon and Weaver 1949) was assessed by treatment to determine overstory species differences among treatments and is a common measure used to assess diversity in forest stands (e.g., Staudhammer and LeMay 2001, D'Amato et al. 2011). Shannon's diversity was used to quantify diversity using species-specific basal area. The Shannon's diversity for each plot was calculated as:

$$H_{\mathrm{BA}} = -\sum_{i=1}^{s} \frac{b_i}{B} \ln\left(\frac{b_i}{B}\right)$$

where H_{BA} is the Shannon's index score for a plot, s is the number of species in the plot, b_i is the basal area of species i, and B is the total basal area on the plot. Additionally, understory species richness was assessed by treatment to analyze the regeneration layer.

Statistical Analysis

All data analysis was completed using R statistical software (R Core Team 2017). One-way analysis of variance was used to compare treatment means calculated from plot means for both short-term and long-term analyses. When significant differences ($P < .05$) were detected, the "agricolae" package in R (de Mendiburu 2017) was used to determine which treatments were different by completing post-hoc least significant difference tests using Bonferroni's corrected P-values.

For the 2017 data in the three remaining treatments (clearcut strips, clearcut patches, shelterwood), nonmetric multidimensional scaling (NMS) ordination was used to explore the relation among species composition and underlying environmental variables. NMS was used because of the relaxed assumptions of normality and linearity (McCune et al. 2002). Data were organized at the plot level, and overstory species basal area was used in the main species matrix. The secondary matrix included structural data to explore the relation among structure, composition, and diversity. Variables included mean dbh, mean maximum dbh, mean minimum dbh, trees per acre, live basal area per acre, Gini coefficient, Shannon's index, understory species richness, CWD, and dead basal area per acre. Autopilot mode (slow and thorough) was selected using Sørensen (Bray–Curtis) distance measurement, and a random starting configuration with 250 runs was completed for both the real and randomized data to determine dimensionality. The means of the coordinates of plots within each treatment were arranged in n-dimensional space using PC-ORD (McCune and Mefford 2011). Environmental variables with an R^2 value greater than 0.2 were considered important to explaining treatment differences (Wilson et al. 2013).

Results

Short-Term Effects (10 Years Post-Treatment)

Pretreatment stand conditions (site index, age, density measures) varied across the experiment prior to treatment (Table 2); however, conditions were not statistically different among treatments (df = 6, $P > .09$). At 10 years, the shelterwood had significantly greater dbh growth than all other treatments at 0.91 ± 0.22 in. (mean ± SD [2.31 ± 0.56 cm]), followed by the single-tree selection (0.75 ± 0.17 in. [1.91 ± 0.43 cm]), which had significantly higher growth than all but the group selection (0.66 ± 0.07 in. [1.68 ± 0.18 cm]) treatments (Table 3).

The control exhibited the largest net basal area increment (24 ± 19 ft^2 ac^{-1} [5.6 ± 4.3 m^2 ha^{-1}]). However, none of the treatments exhibited a significantly different net basal area increment except for the shelterwood treatment, which saw a decrease (–4 ± 12 ft^2 ac^{-1} [0.9 ± 2.8 m^2 ha^{-1}]) after 10 years. Similarly, the shelterwood treatment was the only treatment with significantly greater mortality than any other treatment (29 ± 26 percent of stems). All other treatments had 7 percent or less mortality (Table 3). Examining the cause of mortality in the shelterwood treatment shows that mortality was caused almost exclusively by breakage or tip-up because of wind (Figure 1). Notably, 20 percent of all live and dead basal area in 1960 was lost because of windthrow in the shelterwood treatment. No other treatment saw greater than 2 percent of basal area lost because of windthrow.

Long-Term Effects (57 Years Post-Treatment)

Density

In 2017, the mean basal area was the highest in the shelterwood treatment (136 ± 17 ft^2 ac^{-1} [31.3 ± 3.9 m^2 ha^{-1}]), not significantly different from the clearcut strips (126 ± 21 ft^2 ac^{-1} [29.0 ± 4.9 m^2 ha^{-1}]), but significantly higher than the clearcut patches treatment (113 ± 25 ft^2 ac^{-1} [25.9 ± 5.7 m^2 ha^{-1}]; Table 4). Tree density did not vary by treatment and ranged from 697 ± 122 trees per acre (1,723 ± 302 trees per hectare) in the shelterwood treatment to 805 ± 165 (1,989 ± 407 trees per hectare) in the clearcut patches treatment (Table 4).

Structural Complexity

In 2017, the three treatments had significant differences in all three individual tree attributes representing structural complexity (Table 5). The mean dbh was greatest in the shelterwood treatment (5.8 ± 0.43 in. [14.7 ± 1.09 cm]), significantly larger than the clearcut patches treatment (5.0 ± 0.80 in. [12.7 ± 2.03 cm]); the mean dbh in the clearcut strips treatment did not vary from either treatment (5.4 ± 0.59 in. [13.7 ± 1.50 cm]). The diameter distribution of all three treatments had the greatest numbers of trees in the 5-in. (12.7 cm) class, with the clearcut patches having more trees in smaller-diameter classes. The shelterwood treatment had increased density in the 7-, 9-, and 11-in. (17.8-, 22.9-, and 27.9-cm) diameter classes (Figure 2). The mean height was greatest in the shelterwood treatment at 57.1 ± 4.2 ft (17.4 ± 1.3 m), significantly higher than either clearcut treatment. UCR was lowest in the shelterwood treatment (meaning less live crown) at 0.47 ± 0.11, not significantly lower than the clearcut patches treatment, but significantly different from the clearcut patches treatment (0.54 ± 0.14).

The shelterwood treatment had the highest Gini coefficient—equating to greater size inequality—at 0.150 (±0.016), whereas the Gini coefficient was lowest in the clearcut patches treatment (0.106 ± 0.023)—equating to a more uniform stand structure (Table 6).

Table 2. Mean and range of pretreatment stand conditions (site index, age, basal area, and trees per acre) in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA.

Treatment	No. of plots	Site index (ft at 100 years)		Age (years)		Basal area (ft^2 ac^{-1})		Trees (trees ac^{-1})	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
Thinning	26	42.3	37–46	137	90–180	133.1	118–151	863.1	823–926
Shelterwood	30	53.3	53–54	113	80–160	130.8	126–137	650.7	551–754
CC strips	48	44.6	43–48	135	120–144	124.3	109–134	698.1	539–806
CC patches	43	41.8	41–44	120	70–161	120.0	91–143	783.7	623–905
Group sel.	37	49.2	48–50	99	70–128	133.4	107–150	780.0	681–859
ST sel.	30	44.0	37–49	117	104–138	118.3	98–141	709.3	667–746
Control	23	42.9	35–54	106	70–130	113.2	80–136	723.6	614–796

Note: Conditions are not significantly different across treatments. CC, clearcut; sel., selection system; ST, single-tree.

Table 3. Mean, standard deviation, and range of dbh increment, net basal area increment in residual plots, and percent mortality in peatland black spruce 10 years after initial silvicultural treatment on the Big Falls Experimental Forest, northern Minnesota, USA.

Treatment	No. of plots	Tree dbh increment (in.)			Net basal area increment (ft^2 ac^{-1})			percent Mortality		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Thinning	26	0.60[cd]	0.11	0.25–0.77	20.0[a]	5.7	(60)–42	7.2 percent [b]	11.8 percent	0–61.5 percent
Shelterwood	30	0.91[a]	0.22	0.60–1.56	–4.1[b]	12.2	(62)–32	29.3 percent[a]	26.2 percent	0–78.9 percent
CC strips	37	0.56[cd]	0.09	0.37–0.88	18.7[a]	6.8	(41)–46	7.1 percent[b]	7.6 percent	0–38.7 percent
CC patches	27	0.52[d]	0.11	0.38–0.74	22.6[a]	9.6	(2)–41	4.5 percent [b]	5.0 percent	0–20.3 percent
Group sel.	25	0.66[bc]	0.07	0.55–0.81	21.0[a]	16.0	10–38	4.7 percent [b]	3.5 percent	0–12.3 percent
ST sel.	30	0.75[b]	0.16	0.53–1.13	19.8[a]	25.3	(15)–39	6.7 percent [b]	9.6 percent	0–43.8 percent
Control	23	0.55[cd]	0.12	0.36–0.83	24.3[a]	18.6	12–40	3.8 percent [b]	3.0 percent	0–9.8 percent

Note: Superscript letters denote significant differences among treatments. CC, clearcut; sel., selection system; ST, single-tree; Ht, height; SD, standard deviation.

Measures of deadwood structure, both standing and downed, also resulted in differences between treatments (Table 7). The mean basal area of standing deadwood was around 2 percent of live basal area in all treatments. The shelterwood treatment had the highest mean dead basal area (3.3 ± 3.0 ft^2 ac^{-1}), dead trees per acre (23.5 ± 20.3), and CWD on the forest floor (117.8 ± 103.7 ft^3 ac^{-1}). The clearcut strips treatment did not have significantly different standing deadwood in either category, but did have significantly less CWD (33.8 ± 72.6 ft^3 ac^{-1}) than the shelterwood treatment. The clearcut patches treatment had the lowest dead basal area (0.9 ± 2.1 ft^2 ac^{-1}) and trees per acre (6.2 ± 11.8).

Compositional Complexity

The stand composition measures varied by treatment (Table 6). Species richness of the understory was significantly higher in the shelterwood treatment at 2.94 ± 1.48 species per 1/100th ac (~1/247th hectares) than either clearcut treatment. In the overstory, Shannon's Index for basal area diversity was significantly different in each treatment. The mean value was highest in the shelterwood (0.89 ± 0.19) and lowest in the clearcut patches treatment (0.41 ± 0.18). The lower range of values in both clearcut treatments was 0, meaning some plots were entirely composed of black spruce. The range of the shelterwood treatment was 0.55–1.21. The diameter distribution by species depicts the clearcut patches and strips treatments being dominated by black spruce, with the shelterwood having greater amounts of tamarack, balsam fir, and paper birch in particular (Figure 2).

The NMS ordination resulted in a two-dimensional solution, explaining 98.8 percent of the variation with a final stress of 6.0 (Figure 3). Axis 1 explained 90.6 percent of the variation with Axis 2 explaining the remaining 8.8 percent. Five structural variables had a greater relation to Axis 1 or Axis 2: live basal area, mean dbh, CWD volume, species richness, and Shannon's diversity index had r^2 values > .2. There is stronger clustering of the two clearcut treatments than the shelterwood treatment. More positive scores along Axis 1 are associated with lower species richness and Shannon's diversity index. More positive scores along Axis 2 were associated with greater live basal area, mean dbh, and CWD volume (Figure 3). Environmental variables most associated with any of the three treatments were species richness and Shannon's diversity with the shelterwood treatment (Figure 3).

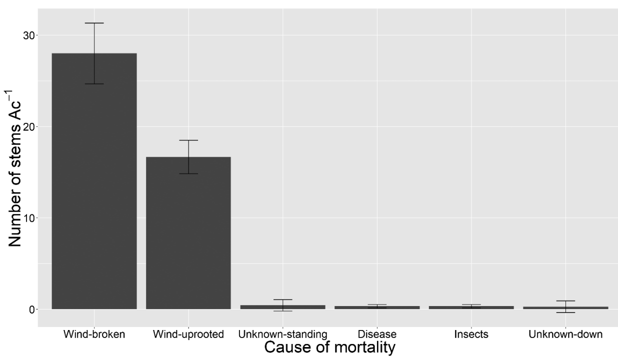

Figure 1. Number of stems per acre experiencing mortality by cause in the shelterwood treatment in lowland black spruce 10 years after initial shelterwood cut in the Big Falls Experimental Forest, northern Minnesota, USA. 19.2 percent of all live and dead basal area was lost because of windthrow. Error bars are one standard deviation.

Discussion

After the first 10 years, the shelterwood treatment saw the largest increase in individual tree diameter growth of residual stems. The gains in individual tree diameter growth in the shelterwood were offset, however, by significant mortality and a net loss in total basal area, almost exclusively caused by wind (Figure 1). However, the primary goal of a shelterwood system is typically not to increase the growth rate of residual trees to be removed in the overstory cut (Montoro Girona et al. 2016), but to serve as a seed source and protection for advance regeneration that is present (Nyland 2007). Measurements collected in 2017 show that the goals of providing a seed source and protection for advance regeneration of the next cohort were accomplished in the shelterwood treatment as it exhibited the greatest basal area despite the original high mortality.

Table 4. Mean, standard deviation, and range of stand density conditions 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA.

Treatment	No. of plots	Basal area (ft^2 ac^{-1})			Trees (Trees ac^{-1})		
		Mean	SD	Range	Mean	SD	Range
Shelterwood	17	136.3[a]	17.1	99–161	697.1[a]	122.1	540–910
CC strips	32	126.2[ab]	21.3	85–170	769.4[a]	184.0	440–1080
CC patches	29	113.0[b]	24.9	76–174	804.8[a]	164.5	490–1150

Note: Superscript letters denote significant differences among treatments. CC, clearcut; SD, standard deviation.

Table 5. Mean, standard deviation, and range of individual tree metrics 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA.

Treatment	No. of plots	dbh (in.)			Ht (ft)			UCR		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Shelterwood	17	5.8[a]	0.43	5.1–6.6	57.1[a]	4.2	50.2–62.8	0.47[b]	0.112	0.25–0.72
CC strips	32	5.4[ab]	0.59	4.3–6.6	46.3[b]	5.9	37.1–62.6	0.54[a]	0.142	0.19–0.90
CC patches	29	5.0[b]	0.80	4.2–7.3	45.7[b]	7.7	36.5–75.0	0.50[ab]	0.138	0.27–0.82

Note: Superscript letters denote significant differences among treatments. CC, clearcut; SD, standard deviation; UCR, uncompacted live crown ratio.

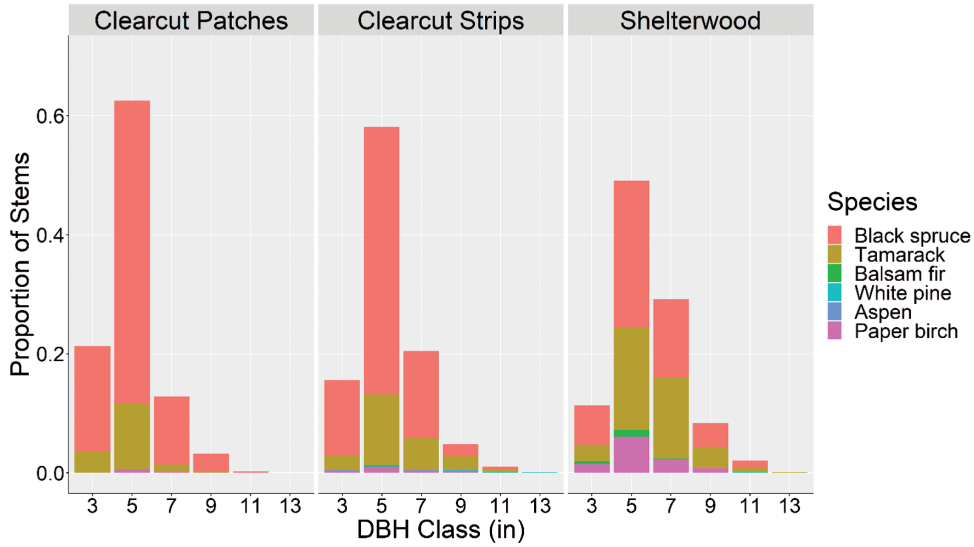

Figure 2. Species mix by diameter distribution in lowland black spruce 50–57 years after final regeneration harvest in three silvicultural treatments on the Big Falls Experimental Forest, northern Minnesota, USA.

Table 6. Mean, standard deviation, and range of the Gini Coefficient depicting tree size inequality and the Shannon's Diversity Index of the overstory in three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA.

Treatment	No. of plots	Gini Coefficient			Shannon's Index (based on basal area)			Regeneration species richness per 1/100th ac (trees <3.6" dbh)		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Shelterwood	17	0.150^{a}	0.016	0.119–0.177	0.89^{a}	0.19	0.55–1.21	2.94^{a}	1.48	1–6
CC strips	32	0.131^{b}	0.029	0.067–0.179	0.54^{b}	0.20	0–0.92	1.81^{b}	0.78	1–4
CC patches	29	0.106^{c}	0.023	0.064–0.151	0.41^{c}	0.18	0–0.66	1.90^{b}	0.72	1–4

Note: Superscript letters denote significant differences among treatments. CC, clearcut; SD, standard deviation.

Table 7. Mean, standard deviation, and range of basal area per acre and trees per acre of dead trees, and volume of coarse woody debris in three silvicultural treatments 50–57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA.

Treatment	*n*	Dead basal area (ft^{2} ac^{-1})			Dead trees (trees ac^{-1})			CWD volume (ft^{3} ac^{-1})		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Shelterwood	17	3.3^{a}	3.0	0–8.7	23.5^{a}	20.3	0–70	117.8^{a}	103.7	0–303
CC strips	32	1.8^{ab}	2.3	0–9.4	12.5^{ab}	14.6	0–40	33.8^{b}	72.6	0–288
CC patches	29	0.9^{b}	2.1	0–9.5	6.2^{b}	11.8	0–50	41.5^{b}	87.4	0–393

Note: Superscript letters denote significant differences among treatments. CC, clearcut; CWD, coarse woody debris; SD, standard deviation.

To decrease mortality of residual trees in a shelterwood treatment, maintaining greater stocking after the initial treatment can decrease wind exposure to residual stems that are susceptible to wind mortality (Nyland 2007). This may be particularly important in the Lake States where high-severity wind events can occur frequently, and in black spruce stands which are highly susceptible to wind-breakage and tip-up because of their shallow-rootedness (Viereck and Johnston 1990, Montoro Girona et al. 2019). However, this may reduce available light to the seedlings and sapling layer. Shifting from a uniform to an aggregated or group shelterwood may decrease windthrow of residuals while accomplishing the regeneration and production goals of a shelterwood (Alexander 2015).

The individual tree selection treatment experienced greater diameter growth over 10 years than either clearcut treatment, and the thinning and group selection treatments resulted in greater diameter growth than the clearcut patches treatment (but not significantly higher growth than the clearcut strips treatment). Although a thinning or individual tree-selection method may not be economically feasible in black spruce stands, the similarity of a group selection method to a shelterwood method in terms of patchiness may result in similar long-term heterogeneous stand conditions while also decreasing initial mortality because residual stems are in groups. Although this study was unable to assess that result, future studies should assess other silvicultural treatments not typically used in black spruce over a long-term time horizon (e.g., Newton 2012, Groot 2014, Lafleur et al. 2016).

Over the long term, the shelterwood treatment resulted in higher basal area and more heterogeneous conditions both structurally and compositionally than the clearcut treatments. Hence, the silviculture treatment may provide additional resilience in the face of disturbance (Holling 1973, Thompson et al. 2009, D'Amato

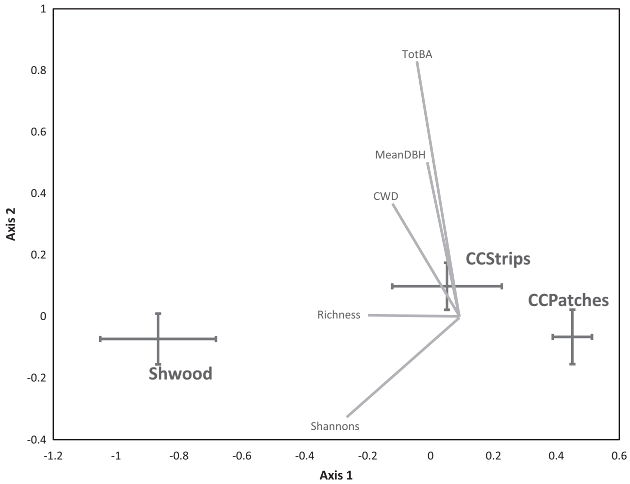

Figure 3. Nonmetric multidimensional scaling ordination displaying the relation between treatments and important environmental variables in lowland black spruce on the Big Falls Experimental Forest, northern Minnesota, USA. Axis 1 explains 90.6 percent of the variation, and axis 2 explains 8.2 percent of the variation. Average scores with associated standard errors for each treatment are displayed. Environmental variables with an r^2 greater than 0.2 are displayed. TotBA, total live basal area; MeanDBH, mean dbh; CWD, volume of coarse woody debris; Richness, species richness of the understory; Shannons, Shannon's diversity index of the overstory; Shwood, shelterwood treatment; CCStrips, clearcut strips treatment; CCPatches, clearcut patches treatment.

et al. 2011), increased and improved wildlife habitat (Deans et al. 2005, Cimon-Morin et al. 2010), and a greater variety of economic products. Larger trees in the shelterwood treatment over the long-term than in either clearcut treatment suggest that rotation ages could potentially be shortened by using a shelterwood system instead of the frequently used clearcut systems.

The wide array of age classes at the time the study was initiated is reflective of the range of age classes in black spruce in Minnesota. Concerns exist about the age of the resource in Minnesota, as 66 percent of Minnesota's black spruce forest, or 1.04 million ac (421,000 hectares), is 60 years of age or older, and only 6 percent is under 40 years of age (Miles 2017). Stands that have not been extensively managed have also escaped stand-replacing fires and are, as a result, older and uneven in age. There has been particular interest in Canada in the use of alternatives to clearcutting methods, where silvicultural systems (i.e., shelterwood, CLAAG, HARP) more closely mimic uneven-aged stand conditions (Groot et al. 2005, Ruel et al. 2013, Pamerleau-Couture et al. 2015). Lowland black spruce in Minnesota, while not having the same extensive research, likely can be managed with these systems. Older stands will have regeneration present in the understory and may provide a means of achieving sufficient regeneration without the use of aerial seeding. However, as Groot et al. (2005) point out, the first implementation of a traditional shelterwood system will likely be the last. After a traditional shelterwood system is implemented, stands will be even-aged, and the use of a shelterwood system is not possible for some time (Groot and Horton 1994). However, an irregular shelterwood system may be used to maintain or convert stands to uneven-aged in order to maintain or increase structural heterogeneity (Raymond et al. 2009).

Another concern regarding Minnesota's black spruce cover type is the presence of eastern spruce dwarf mistletoe (*Arceuthobium pusillum*). Dwarf mistletoe is a parasitic plant that forms witches brooms on black spruce branches that reduces growth and eventually kills infected trees, and is an important disturbance consideration in lowland black spruce throughout its range, and particularly in Minnesota (Anderson and Kaufert 1953, Baker et al. 2006, Baker et al. 2012). It is estimated that 11–55 percent of black spruce stands in Minnesota are infected with dwarf mistletoe (Baker et al. 2012). Management recommendations call for clearcutting all stems over 5 feet (1.5 m) tall with a buffer strip of up to 130 feet (40 m) around infections to ensure latent infections are completely removed (Johnston 1977b, Baker et al. 2006). On the Compartment Study, mistletoe was present on only two trees in the initial measurement and not found in 2017, and was not a major component in any of the treatments. Given standard management recommendations and mistletoe infection dynamics, shelterwood and selection methods would not be viable in infected stands. However, patch or strip clearcuts may be successfully implemented in mistletoe-infected stands if a wide enough buffer is cut to remove possible latent infections.

A traditional clearcutting system using complete removal of the overstory over a large area (i.e., not clearcut strips or patches) was not installed at the outset of this study, and the control treatment was lost because of unrelated harvesting. Therefore, direct comparisons to unmanaged stands or stands using traditional clearcutting were not completed. However, clearcutting has been shown to result in taller regeneration 8 years after harvesting than CLAAG, likely because of increased soil disturbance (Lafleur et al. 2010), whereas clearcutting followed by prescribed burning resulted in higher growth rates than traditional clearcutting and increased stem density over time compared to CLAAG and clearcutting only after 13–22 years (Renard et al. 2016). Future studies should assess alternative silvicultural treatments in comparison with both traditional clearcutting and control treatments over long time horizons. Additionally, all regeneration on the study was natural. Since aerial seeding is frequently used to facilitate regeneration in lowland black spruce, further study should assess stand structure, composition, and stocking of alternative silvicultural treatments and traditional clearcutting with and without aerial seeding.

Conclusion

This 67-year-old study helps to fill key gaps in the understanding of stand dynamics in lowland black spruce treated with alternative silvicultural methods in the Lake States, USA. The results of this study support the use of shelterwood systems in lowland black spruce in northern Minnesota, particularly in older stands with advance regeneration that are free of eastern spruce dwarf mistletoe. A shelterwood system may fulfill key management objectives over time by providing protection and a seed source while increasing residual tree growth in the short-term, and increasing structural and compositional complexity and diversity and stand basal area over the long-term. Patch and strip clearcuts may be more viable in cases where mistletoe is present, and potential for windthrow is high. There is additional need to understand long-term dynamics of uneven-aged regeneration systems. Alternative silvicultural systems, including clearcut strips, clearcut patches, and shelterwood systems, could serve as additional management regimes to consider in promoting healthy lowland black spruce forests.

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